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THE UNIVERSITY OF ALBERTA

EFFECT OF STEAM CURING AT ATMOSPHERIC PRESSURES UPON CONCRETE STRENGTHS

A DISSERTATION

SUBMITTED TO THE SCHOOL OF GRADUATE STUDIES IN
PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE
DEGREE OF MASTER OF SCIENCE

FACULTY OF ENGINEERING
DEPARTMENT OF CIVIL ENGINEERING

by

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Under the direction of
Professor L.A. Thorssen

University of Alberta
Edmonton, Alberta.

March 10, 1952

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The undersigned hereby certify that they have read and recommend to the School of Graduate Studies for acceptance, a thesis entitled "Effect of Steam Curing at Atmospheric Pressures upon Concrete Strengths", submitted by Charles Henry Weir, B.Sc., D.L.S., A.L.S., in partial fulfilment of the requirements for the degree of Master of Science.

DATE

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Preface

Steam curing is being introduced into the concrete masonry industry more and more every day. This investigation was carried out to elucidate some of the problems arising in steam curing and to determine some of the effects of steam curing upon the concrete. Also, since there has been little known work done concerning the effect of steam curing at atmosphereic pressures upon the bond between concrete and steel, a short investigation was carried out to more or less pave the way for more investigations of this nature to be carried out at the University of Alberta.

One of the main items of this investigation was the building of a steam curing kiln suitable for laboratory use. This part of the investigation was performed in conjunction with Mr. D.A. Bernard, B.Sc. When the steam kiln was built and functioning properly, we both branched out into separate investigations.

A total of 300 cylinders was made and tested and 24 pull-out tests performed. The conclusions reached from these tests are listed on pages (90) and (127).

The author is deeply indebted to Professor L.A. Thorssen for his valuable suggestions and guidance. Appreciation is also due to Mr. L.F. Fead and Mr. G.C. Malmberg, laboratory technicians, for their advice and assistance in keeping the equipment functioning at all times

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HISTORY

The demand for concrete masonry units has approximately doubled within the last ten years, creating an unprecedented burden in the concrete masonry industry. Plants have been enlarged, new plants established; new and more efficient equipment has replaced the old every few years; labor saving methods have been installed and production processes speeded up - all in an effort to keep output abreast of demand. This speed up has made the curing cycle the object of critical examination and research.

In the modern factory production of concrete products it is necessary to speed up the curing cycle from a matter of weeks to a matter of hours. This necessity arises for a number of reasons; to release moulds and pallets as quickly as possible; to generally syncronize the curing cycle with the manufacturing process; and to put the finished product on the market as soon as possible to avoid having tp provide extensive storage space. In the speeding up of the curing cycle there must be no sacrifice in the quality of the finished product; if anything, the quality of the finished product should be improved.

Naturally, the best way to cure concrete is by warmth and moisture, therefore the speeding up of this process lends itself to steam curing. Some acceleration of setting and

curing can be achieved by chemical means, but steam curing is more effective and susceptible to accurate control. Considerable amount of work has been done in the steam curing of concrete but the results are in some respects contradictory and not easily applied to commercial practice. Some of the earliest work was done in 1911, by R.J. Wig and later a few investigations have been made in commercial kilns, Mansfield (2) Nurse (3). From a study of the literature, steam curing lends itself to three main processes: (1) High Pressure, (2) Low Pressure Continuous and (3) Low Pressure Intermittent.

High Pressure Process

High pressure steam curing consists of curing blocks in high pressure vessels at about 125 psi and temperatures in the vicinity of 350 degrees - 360 degrees Fahrenheit. Excess water is kept in the chamber, and control is therefore achieved by regulation of either temperature or pressure alone. The steaming period, 8 to 10 hours, is compartively short but the process is intermittent.

In A.C.I. Committee 716 (5) the following conclusions were reached regarding high pressure steam curing:

1. Concrete masonry products can be produced by high pressure steam curing methods and ready for use within 24 hours after molding.
2. High pressure steam curing is complete without cracks and without substantial change in shape or size.
3. High pressure steam cured units are substantially

in a drier condition and lighter in color than moist cured units, and give a clear ring when tested with a hammer.

4. Compressive strength of high pressure steam cured units at one day is at least equal to that of moist cured units at 28 days.
5. High early strength of high pressure steam cured units is permanent.
6. High pressure steam curing treatment tends to stabilize unsound materials that might otherwise result in popping or spalling in service.
7. High pressure steam curing develops increased resistance to sulfate action.
8. High pressure steam curing (especially in the presence of silica) practically eliminates leaching and efflorescence.
9. The strength of high pressure steam cured units is influenced by the amount and character of siliceous material in the mix but to a lesser degree in lean mixes than in rich and wet mixes.
10. The shrinkage of high pressure steam cured units, in drying from a saturated condition to equilbrium with air in a heated building, is about 50 per cent less than in moist cured units.
11. High pressure steam curing results in lower bond stress between steel and concrete.

One can see from the above that the high pressure steam curing process does a good job but the equipment required is very expensive to install and operate. Also high pressure steam curing tends to make some aggregates very brittle. High pressure curing can be recommended only when it is important to reduce shrinkage or to increase sulfate resistance, or where the maximum strength is desired.

The main difference between high and low pressure curing as given in Nurse (3) are; in high pressure curing,

1. A more rapid increase in strength occurs owing to a higher temperature.
2. With certain aggregates a lime silica reaction may take place between the cement and aggregate, and strengths may be developed in excess of that predictable from the effect of increased hydration alone.
3. A reduction in initial drying shrinkage and the reversible wetting and drying movements occur.
4. An increased resistance to sulfate attack is obtained.

Low Pressure Continous Process:

For the mass production of concrete products the continous process has an advantage over the intermittent process for obvious reasons. The operation of the plant can be regulated so that there is a continous process from the time the blocks are made until they have been cured and put into the storage yard. The curing kiln usually consists of a long tunnel. The raw blocks are put in one end and the

cured blocks come out of the other end. The tunnel may have a temperature gradient at each end, and in this case the doors may be left open without undue loss of heat. The doors on a shorter high temperature tunnel may be fitted to conserve heat and in this case the haulage is usually intermittent. In this process a day and night shift is necessary for utmost in plant efficiency.

Low Pressure Intermittent Process

The low pressure intermittent process is carried out in a battery of curing kilns. The kilns are filled during the day and steamed during the night. The heating, steaming and cooling or soaking period are usually controlled automatically. There has been no definite conclusions reached yet, as to suitable lengths of time and temperatures for these cycles. A number of investigations has been carried out to ascertain the effect of different cycles and temperatures upon the concrete products. All of these investigations show that there should be a waiting period after molding, before the concrete is subjected to steam curing. The length of this waiting time varies, but 2 to 6 hours is usual.

Difficulties have arisen in the building of suitable kilns for steam curing. It is necessary to know the atmospheric conditions within the kiln and the effect of different kiln atmospheres on the curing of the concrete products. The kiln must be built and operated properly to

obtain good curing conditions. Among the problems associated with low pressure steam curing are: the effect of steam curing concrete units, building of a suitable kiln, establishing the proper steaming cycles and curing temperatures, etc. When these problems have been solved the final result will be one of the greatest advances in manufacturing procedure in the concrete masonry industry.

FACTORS TO BE CONSIDERED IN STEAM CURING

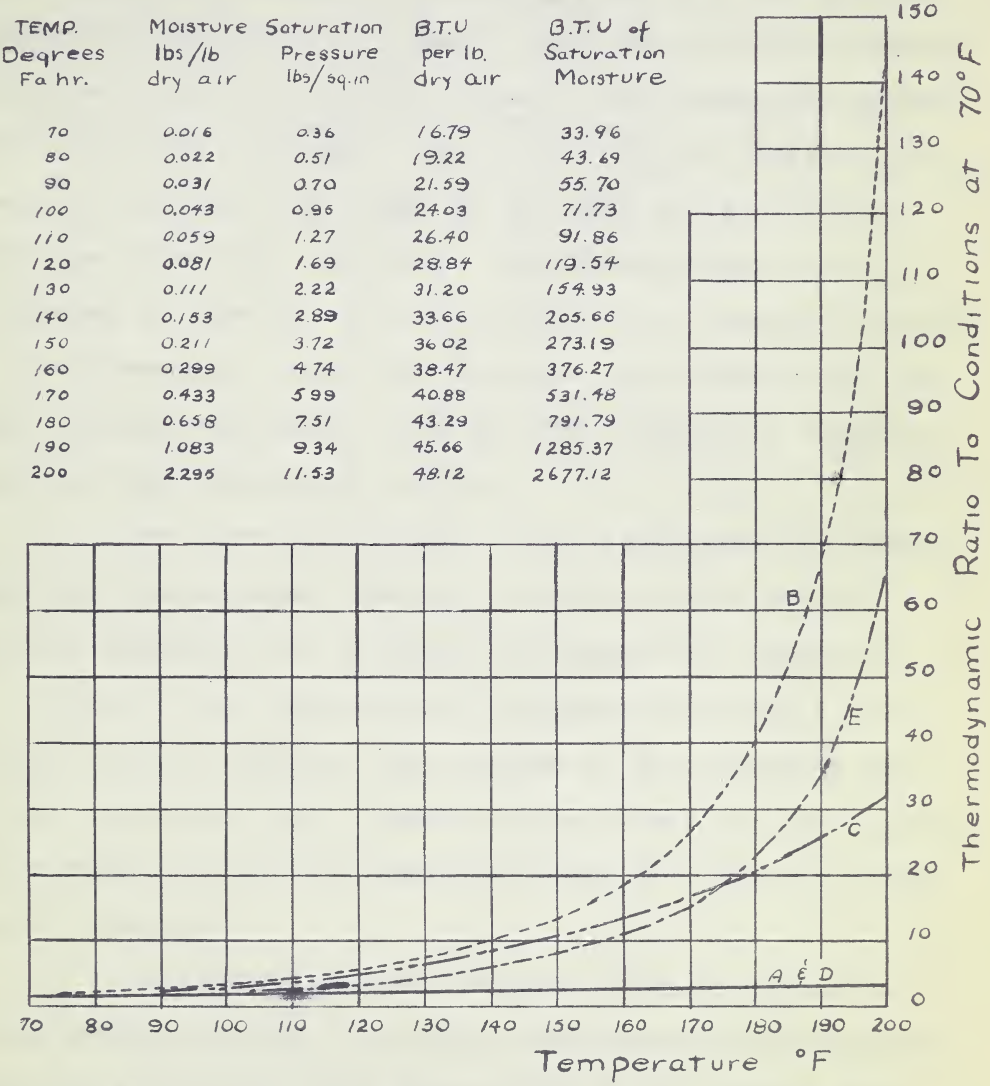
The hardening process is a chemical reaction between the cement and water known as hydration, and this chemical action is controlled by time, temperature and moisture, commonly known as curing. Faulty curing will cause incipient failure and limited life to the concrete irrespective of care taken in selection of aggregates, methods of placing or molding etc. Sufficient moisture must be in immediate contact with the cement for the normal products of hydration to develop. When a concrete block is cured in a steam kiln three atmospheres should be considered, atmosphere outside the kiln, atmosphere in the kiln and the atmosphere within the block. Of importance in each of the three atmospheres are relative humidity, the temperature, vapor pressures and their relation to one another. Is moisture being added or taken away from the concrete block as the curing process is going on? If moisture is being taken away from the block, is their still enough left for hydration?

Properties of Moist Air

From a study of properties of air at various temperatures one can understand the difficulties of maintaining moisture in contact with cement during a high temperature curing cycle in a kiln at atmospheric pressure. Consider the data in Figure I selected from the tables in American Society of Heating and Ventilating (8) with points out the

THERMODYNAMIC PROPERTIES of MOIST AIR

TEMP. Degrees Fahr.	Moisture lbs/lb dry air	Saturation Pressure lbs/sq.in	B.T.U per lb. dry air	B.T.U of Saturation Moisture
70	0.016	0.36	16.79	33.96
80	0.022	0.51	19.22	43.69
90	0.031	0.70	21.59	55.70
100	0.043	0.96	24.03	71.73
110	0.059	1.27	26.40	91.86
120	0.081	1.69	28.84	119.54
130	0.111	2.22	31.20	154.93
140	0.153	2.89	33.66	205.66
150	0.211	3.72	36.02	273.19
160	0.299	4.74	38.47	376.27
170	0.433	5.99	40.88	531.48
180	0.658	7.51	43.29	791.79
190	1.083	9.34	45.66	1285.37
200	2.295	11.53	48.12	2677.12



—— Curve A – represents temperature ratios
----- Curve B – moisture requirements for dry air saturated
-·-·- Curve C – shows progressively increasing saturation pressures
—— Curve D – indicates heat content of dry air
—·— Curve E – heat content of moisture in dry air saturated

Fig 1

amount of moisture necessary at high temperatures to maintain one hundred per cent humidity.

The thermodynamic properties of saturated air are listed in 10 degree increments from 70 to 200 degrees Fahrenheit, inclusive. Column B shows the moisture requirements per pound of dry air; Column C, the saturation pressures in pounds per square inch; Column D, the enthalpy per pound of dry air; and column E, the heat content of the moisture of dry air saturated. The thermodynamic data is tabulated to show the decidedly progressive demands in moisture requirements, saturation pressure, heat content of dry air saturated as against straight line demands in temperature and heat content of dry air.

The curves in Figure 1 were established by plotting each thermodynamic property from 70 degrees to 200 degrees Fahrenheit in 10 degree increments and expressed as a ratio to the condition at 70 degrees Fahrenheit. The curves further emphasize the problem of maintaining a saturated atmosphere when elevated temperatures are contemplated for accelerated concrete masonry curing in a kiln at atmoshereic pressure.

As another example, suppose a curing system is being employed having a dry bulb temperature of 130 degrees Fahrenheit and a wet bulb temperature of 130 degrees Fahrenheit which is 100 per cent relative humidity and 100 per cent saturated. If the dry bulb temperature were raised to 180 degrees Fahrenheit without the addition of any more

moisture, using the formulae and tables in American Society of Heating and Ventilating (8), the resulting wet bulb temperature would be 133 degrees Fahrenheit and the relative humidity 29.5 per cent. Similarly at 200 degrees Fahrenheit the relative humidity would be 19.2 per cent.

Atmospheric Conditions in the Steam Kiln

The atmospheric conditions within the kiln and the air outside the kiln are different at all times during the curing cycle. Suppose the kiln temperature is 160 degrees Fahrenheit and the outside temperature is 70 degrees Fahrenheit and further that both atmospheres have 100 per cent relative humidity. Then the vapor pressure within the kiln is 4.74 pounds per square inch and the vapor pressure outside the kiln is 0.36 pounds per square inch, giving a pressure differential of approximately 13:1.

If the outside air had a relative humidity of 50 per cent, which is more likely to be the case, then the pressure differential would be still greater. Under these conditions moisture would be forced out of the kiln. This shows the necessity for having a well built kiln when considering high temperature, high humidity curing of concrete products.

Now consider the atmospheric conditions within the concrete block and the kiln atmosphere. If the vapor pressure within the concrete unit is greater than the vapor pressure in the kiln atmosphere, then moisture will move from

the unit to the kiln air. When a concrete block is first made excess water is usually present, therefore when the block is first put into the kiln the relative humidity within the block is very close to one hundred per cent. Unless the relative humidity of the kiln air is very close to one hundred per cent, there will be movement of moisture from the block to kiln air. But if the temperature of the kiln air is raised, temperature of the block will lag behind the temperature of the kiln air. If the relative humidity of the kiln air is kept near 100 per cent, moisture will move from the kiln air into the block even though the relative humidity of air within the block is 100 per cent. For example suppose the temperature of the kiln air is 165 degrees Fahrenheit and of the block 160 degrees Fahrenheit, and the relative humidity of the air within the block is 100 per cent and of the kiln air is 95 per cent. By using the table in American Society of Heating and Ventilating (8), the vapor pressure in the block is 9.6556 inches of mercury and the vapor pressure of the kiln air is 10.322 inches of mercury. This shows that during the heating cycle it is not necessary to have a relative humidity near 100 per cent. In the above example a relative humidity of 87 per cent would still be quite satisfactory.

If the temperature of the kiln remained constant for a considerable period, the kiln air temperature and the block temperature would tend to equalize; but heat produced within the block due to the hydration of the cement would

bring the block temperature slightly above that of the kiln air. From Figure 1 it can be seen that the higher the temperatures, the greater will be the difference between the saturation pressures for the same difference in temperature. Therefore if elevated temperatures are maintained for long periods, the moisture required for hydration of cement will be removed from the block regardless of the relative humidity of the kiln air, but the higher the relative humidity of the kiln air, the smaller is this movement of moisture.

In the cooling or so-called soaking period of the steaming cycle, moisture will move from the block into the kiln air. The temperature of the block will be higher than the temperature of the kiln air. The temperature difference will be greater for faster rates of cooling. This would indicate that the rate of cooling should be controlled, and procede at a very slow rate. To illustrate these temperature differences see Figure 2 obtained from Mansfield (2) and Shedeler and Chamberlin (9).

The rate of temperature rise and rate of cooling must also be controlled to prevent thermal shock. If the rate of temperature rise or fall is too great, cracking will result from the differential stresses set up by the large temperature gradients. This will have a greater effect on the larger concrete units; also the shape and position of the reinforcing will have an effect when the possibility of thermal shock is considered. The average rate of temperature rise in most plants is above ½ degree Fahrenheit per minute and the

cooling rate is somewhat slower.

From the discussion so far an ideal steam cycle might be proposed such as the following: Heat to a fairly high temperature quite quickly, for example ½ degree Fahrenheit per minute from 70 degrees Fahrenheit to 150 degrees Fahrenheit; then increase from 150 degrees Fahrenheit to 180 degrees Fahrenheit, at a rate of heating that will keep the temperature of the kiln air just above the temperature of the block. Suppose that this is kept up for 12 hours and then the cooling cycle is started. This cycle could be adjusted somewhat to coincide with the plant operations and other factors in the operation of a concrete products plant. With a cycle like this, one would have to be able to control the kiln temperature very accurately, and because of this some manufactures might stray away from this type of steaming cycle. However, with the number of automatic devices developed today, it should not be hard to control automatically a cycle such as this.

Phase Equilibrium

It has been explained why a kiln atmosphere of high relative humidity is required but now it is necessary to consider how to obtain this type of atmosphere. From thermodynamics it is indicated that to have a condition of equilibrium existing below 212 degree Fahrenheit and at atmospheric pressure, it is necessary to have a system containing steam, water and air. This means we must have air, water and steam entering the kiln.

The above can be explained better in terms of

Temperature Conditions During Curing

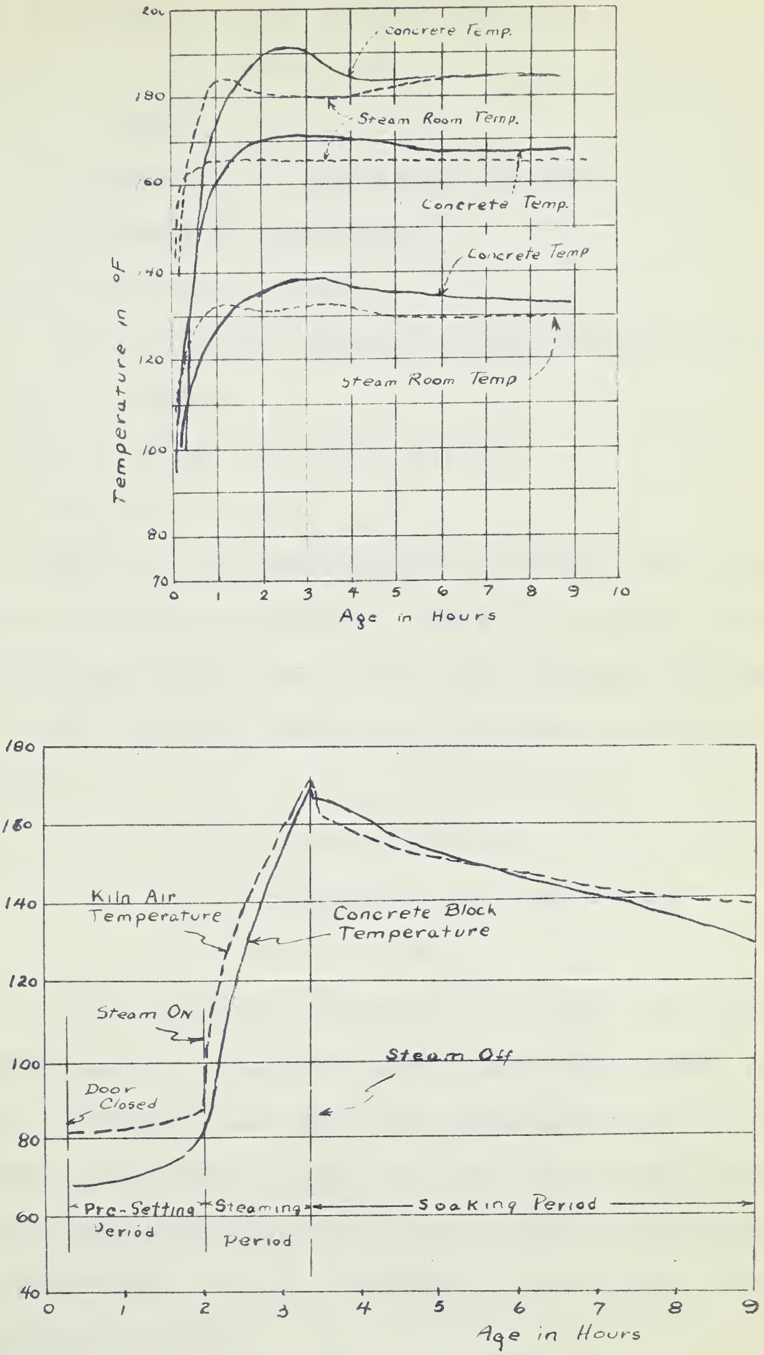


Fig. 2

phase language. The number of degrees of freedom or variance of a system is given by the equation:

$$V = C + 2 - P$$

where

V = variance or degrees of freedom

C = number of components

P = number of phases.

In the case of steam and water entering the kiln,

$C = 1$ (Water)

$P = 2$ (Water and water vapor)

$V = 1 + 2 - 2 = 1.$

Thus we have one degree of freedom, and if we stipulate atmospheric pressure, there is a unique temperature for equilibrium conditions, namely 212 degrees Fahrenheit.

Now consider steam, air and water entering the kiln, where

$C = 2$ (Water and air)

$P = 2$ (Saturated air and water)

$V = 2 + 2 - 2 = 2.$

We now have two degrees of freedom, and if we stipulate atmospheric pressure we still have one degree of freedom left, so that we can vary the temperature and still have equilibrium conditions. Thus, to have saturation conditions existing at atmospheric pressure and temperatures below 212 degrees Fahrenheit, it is necessary to have steam, water and air entering the kiln.

Carbonation

The carbonation of the concrete is another factor that should be considered in curing of concrete masonry. When sufficient moisture is not present with Portland cement during the curing cycle, carbon dioxide from the kiln atmosphere is absorbed by the concrete and this can be detrimental or beneficial. If the carbonation occurs before the period when the Portland cement hydration compounds are being formed, it is detrimental, but if it occurs following the hydration, it is beneficial. As the concrete becomes successively drier, the rate of carbon dioxide absorption becomes increasingly greater. The detrimental effect is to make the concrete units brittle, although the strengths may be favorable. In view of the harmful effect of carbonation during hydration, caution should be observed in selecting a curing method that develops heat and moisture, particularly when the system being considered causes the products of the fuel combustion to become part of the kiln.

Drying of Blocks

If the concrete block is to be put into almost immediate use, it is desirable to have a dry block. If the block has a high moisture content when put into use, there will be considerable shrinkage which is detrimental to the resulting structure. As a result of this some plants use the last part of the cooling cycle as a drying cycle. This is quite feasible, because as the block temperature cools it will be higher than the kiln air temperature, and due to the

vapor pressures moisture will be forced from the block to the kiln air. If the relative humidity of the kiln air is reduced, the movement of moisture from the block will be still greater.

When a temperature of 221 degrees Fahrenheit is maintained, then chemical compounded water is driven from the hydrated cement, which in turn tends to destroy the cement gel. For this reason it is advisable to refrain from using temperatures in excess of 200 degrees Fahrenheit for atmospheric pressure curing. Similarly, when a plant intends to use dry heat for reducing moisture content, the same caution must be observed to prevent loss of chemically compounded water.

Size of Concrete Block

Another problem that will arise is the size of the concrete block or concrete specimen. The rate at which heat is taken up will depend upon the specific surface area, i.e. the surface area divided by the volume. Specific surface area for a 6 by 12 cylinder will be 0.83, for a 4 by 8 cylinder 1.24 and for a 2 by 4 cylinder 2.5. If all the other factors in the units are kept constant but the size, then the temperature lag in the large cylinder will be greater than in the small cylinder during the heating and cooling periods in the steaming cycle. If the temperature of the kiln air were held constant for a considerable length of time, the temperature difference between the kiln air and the cylinder could be greater for the large block than the smaller block.

That is, the heat produced by the hydration of the cement would be lost more readily by the small block than by the large block. The vapor pressure differences in the two blocks would correspond to the temperature differences. As an example, suppose the kiln air were at a temperature of 180 degrees Fahrenheit, the smaller cylinder at a temperature of 182 degrees Fahrenheit, and the large cylinder at a temperature of 184 degrees Fahrenheit; then (assuming 100 per cent relative humidity) the corresponding vapor pressures (American Society of Heating and Ventilating (8)) would be 15.294, 15.985, and 16.702 inches of mercury. As was said before, the greater the vapor pressure differences, the greater is the tendency for moisture to move from the block to the kiln air; however, in this case, the moisture in the large block would have further to travel than in the small block, so that these effects would tend to cancel one another out. From these considerations a prediction might be made that the smaller block would be cured slightly better than the larger blocks, but this remains to be seen.

Type of Aggregates

The effect of low pressure steam curing upon the different types of aggregates will not be so great as the effect of high pressure steam curing. The presence of excess amounts of calcium carbonate will affect the strength when low pressure steam curing is considered, especially at the higher temperatures. Dense aggregates and the concrete made from them will have a larger heat capacity and

therefore take longer to heat, but the thermal conductivity of the denser mixes will be greater and this will probably offset any effects due to heat capacity.

Design of Mix

The design of the concrete mix should have little effect upon the effectiveness of steam curing since steam curing primarily affects the hardening process or the hydration of the cement. However where the water cement ratio of the mix is very low, that is to a point where there is insufficient moisture for hydration to take place, it will increase the necessity of having a condition in the curing chambers so that moisture will move from the kiln air into the block. Also where the mix design results in a dense concrete, the effect will be the same as that discussed under aggregates.

LABORATORY EQUIPMENT

1. Steam Curing Cabinet for the Laboratory

Introduction

A steam curing cabinet to be used in investigations on the effect of steam curing at atmospheric pressures must be susceptible to accurate control, and also the individual elements which go to make up a steam curing kiln must be controllable. From the thermodynamic considerations laid out in the previous sections, it is necessary to have steam, air and water entering the kiln to obtain the required high relative humidity of the kiln. The steam supplies the necessary heat and, although it can be replaced by other means, for this investigation steam was the most practical. Also it is more economical and practical to use standard building materials wherever possible in the construction of the steam kiln.

Following are some of the necessary requirements in an experimental steam kiln:

(1). To be able to obtain an atmosphere in the kiln of very high relative humidity over a wide temperature range. The temperature range in this investigation was from 75 degrees Fahrenheit to 185 degrees Fahrenheit.

(2). To be able to control the rate of temperature rise and temperature fall and to be able to hold a constant temperature for considerable

lengths of time. That is, to be able to subject the concrete specimens to different curing cycles.

(3). To provide a method of measuring and recording the temperature within the kiln and within the concrete units over long periods of time.

(4). To have uniform temperature throughout the kiln.

(5). To be able to measure the pressure within the kiln to check whether the pressure is atmospheric.

(6). To provide a means of measuring the weight changes of the concrete unit during the curing cycle.

(7). To provide a means of measuring the relative humidity within the kiln.

Construction of the Steam Kiln

Figures on pages (26), (27), (29) and (30) illustrate the steam kiln in different views. The kiln was built out of brick and concrete. It consisted of a cabinet 5 feet by 3 feet by 2½ feet. The walls were made of a single layer of bricks, the roof consisted of a concrete slab 1½ inches thick and the floor consisted of a concrete slab 2 inches thick. Both the roof and floor slabs were reinforced with chicken wire. A single tapered door 28 inches square provided access to the cabinet. Holes were left in the central portion of both ends to provide an entrance for the steam and

an exhaust. Holes were left in the roof slab to provide passage ways for the thermocouple leads and other equipment. The inside surface of the kiln was lined with "Horn Kiln Liner", an asphaltic type kiln liner compound sold by A.C. Horn, 821,Queen Street E, Toronto 8. The interior was divided into top and bottom sections by an open shelf of 2 by 4 slats supported on a aluminum frame. Figures (3), (6) and (7) on pages (26), (29) and (30) illustrate provisions made to obtain the first requirements of the steam kiln. Steam, air and water were introduced into the kiln. The amount of each material necessary was not computed but was put into the kiln in such quantities that the required atmosphere was likely to be obtained. The air, water and steam entered the mixing chamber first. The air came from an air supply line delivering air at 25 pounds per square inch. The steam came from the radiator heating system, using exhaust steam from the University of Alberta power plant supplied at 3 to 4 pounds per square inch. The water came from the city water supply and entered the mixing chamber through a fog nozzel of the type used in air conditioning systems and rated at 0.65 gallons per hour at a pressure of 40 pounds per square inch. The mixing chamber consisted of a one-inch diameter standard four way pipe fitting. From the mixing chamber the resulting atmosphere went into the steam kiln through a one inch diameter pipe. An extra fog nozzel was placed on top of the kiln to ensure a high relative humidity.

The second requirement of the steam kiln was fulfilled by regulating the steam supply to the mixing chamber. A "Powers" type "T" direct acting, air operated, thermo regulator and $\frac{1}{2}$-inch valve capable of delivering 88 pounds of steam per hour at a pressure of 4 pounds per square inch was used. The valve was connected between the steam supply and the mixing chamber and a by pass valve provided for use if necessary (see Figure (7), Page (30)). The thermo regulator was placed on top of the kiln with the thermostatic temperature rod extending into the cabinet.

The regulator employs a copper bulb and invar rod as the sensitive element. With a change in temperature at the bulb, a valve inside the regulator is positioned to vary the air pressure to the diaphram which operates the valve.

The thermo regulator could be set at the desired temperature by the adjusting knob, but in order to obtain the steaming cycles automatically it was necessary to build a remote control mechanism. This remote control devise consisted of a small electric motor which turned a cam very slowly (approximately one revolution per day). The cam actuated a rack and pinion assembly which in turn operated the adjusting knob on the thermo regulator. The cam was so shaped that any desired curing cycle could be obtained. Finer adjustments of the steaming cycle were obtained by providing a cam follower push rod which was adjustable. A schematic sketch of the remote control mechanism is given in Figure (5), Page (28). A different cam was made for each

cycle so that when it was decided to run the steam kiln at a different cycle it was necessary to change the cams. The mechanism provided a large range of temperature control, allowed an accurate reproduction of any curing cycle, did away with manual control except for the initial adjustments and was relatively simple.

A "Brown Temperature Recorder" provided the answer for the third requirement for a curing kiln to be used for experimental purposes. The Brown Recorder measured and recorded temperature by the use of thermocouples. A total of sixteen thermocouples could be connected to the recorder and temperature records would be kept for the sixteen thermocouples. (The operation of the "Brown Temperature Recorder" is completely outlined in "Manual of Maintenance and Operation" supplied with the instrument.)

To obtain the average temperature of the kiln during the curing cycles, eight thermocouples were placed in the kiln and then connected to a single lead. The resulting temperature was the mean of eight temperature readings throughout the kiln.

The fourth requirement was provided by using a steam manifold and a baffle plate. The steam manifold was placed $\frac{1}{2}$-inch above the floor. The manifold was connected to the mixing chamber by a one-inch pipe. The manifold was made from one-inch pipe and contained two rows of holes discharging down at an angle of 45 degrees. The holes had a diameter of 3/16-inches and were 7-inches centers. Each

row contained 7 holes. The atmosphere from the mixing chamber entered the kiln through these holes. The baffle plate was positioned at the exhaust end of the kiln. The baffle plate was made of **transite** board $\frac{1}{2}$ inch thick with 150 - $\frac{1}{2}$ inch diameter holes. The baffle board was placed 8 inches from the end of the kiln. The exhaust pipe came out of the kiln at mid height in the centre of one end of the kiln and continued for 140 feet to a waste water sump. This lay out gave a fairly uniform temperature throughout the kiln. The temperature at the corners of the kiln varied somewhat but no cylinders were placed here. The temperature variation was within about 5 degrees Fahrenheit.

It may be noted here that at first two baffle plates were used (one at each end of the kiln) with the steam coming in at mid height in the centre of the end of the kiln opposite to the exhaust. The steam came direct from the mixing chamber and not through the manifold. With this method the temperature variation throughout the kiln was too great. The variation was about 20 degrees Fahrenheit. The use of the manifold proved much better.

A "U" type water-filled manometer was used to measure the pressure inside the kiln. It was placed at the discharge end of the kiln. A rubber tube connected the manometer to the inside of the kiln. At first it was thought that the kiln pressure would probably be built up by a discharge pipe 140 feet long but this was not so. The greatest pressure difference recorded was about 0.05 pounds per square

STEAM KILN FRONT VIEW

Scale 1" = 1'

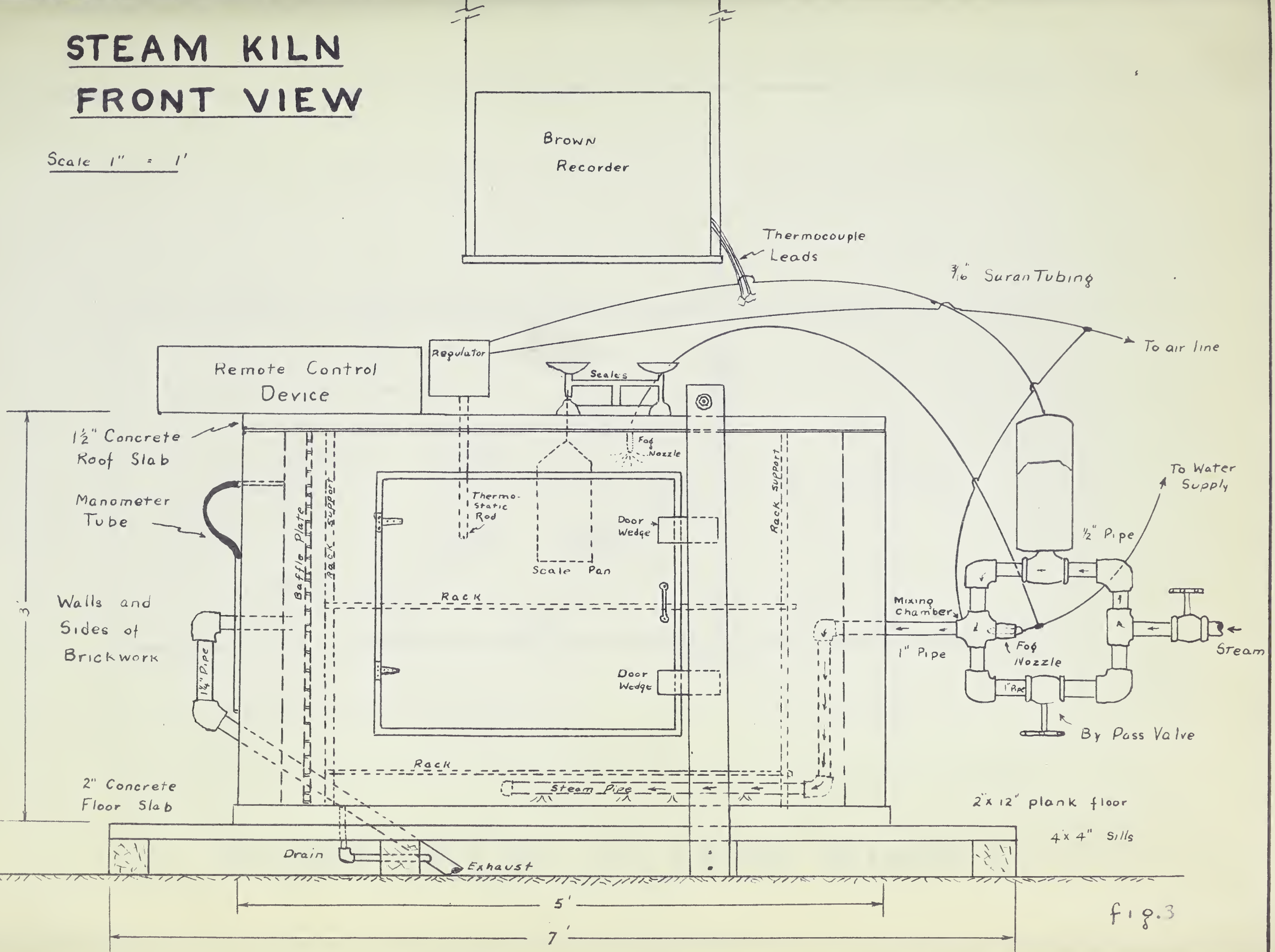
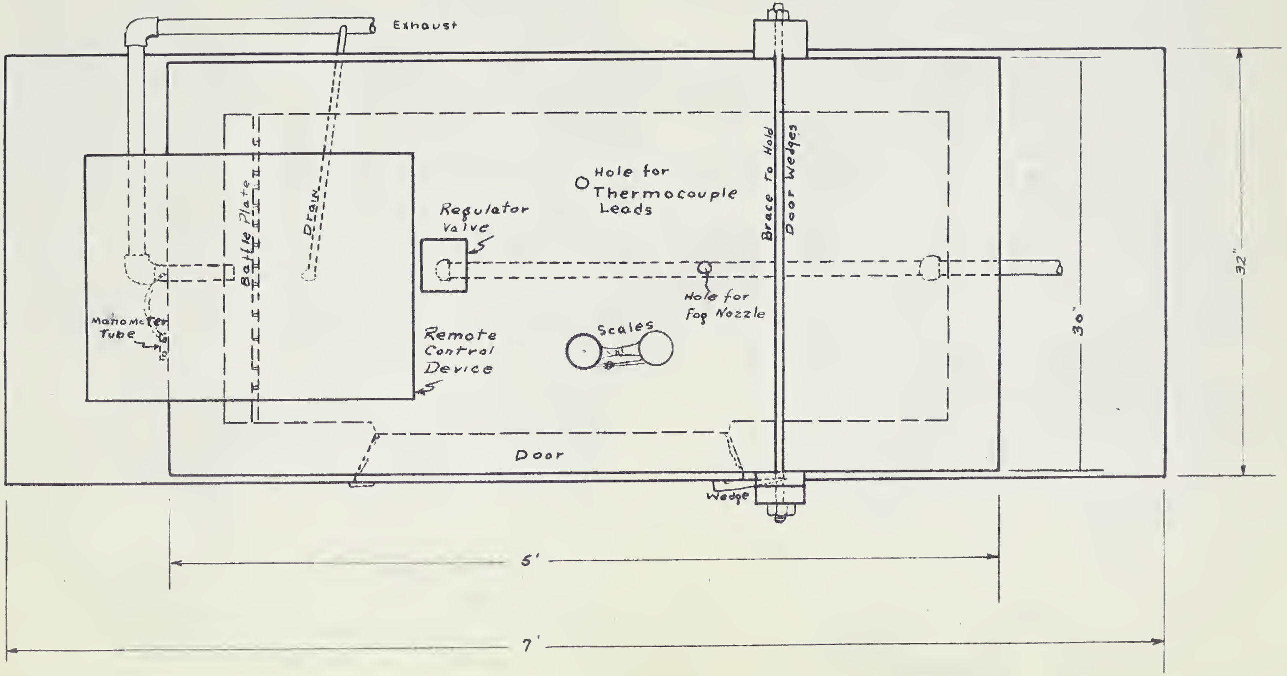


fig.3



PLAN VIEW STEAM KILN

Scale 1 inch = 1 foot

Fig 4

SCHEMATIC DIAGRAM OF REMOTE CONTROL [illegible]
STEAM CURING KILN —

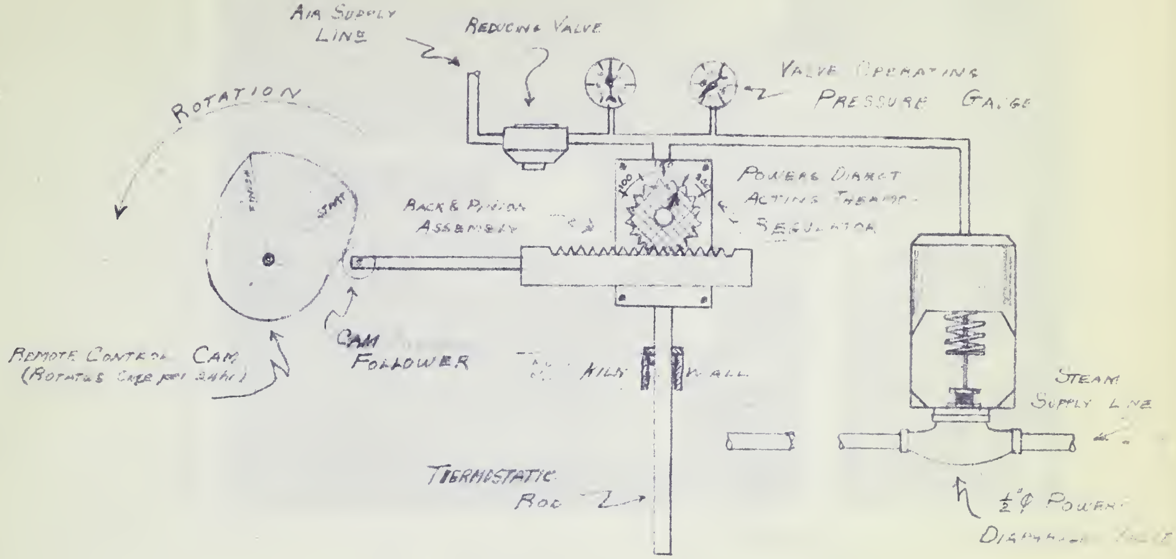

AIR SUPPLY LINE
REDUCING VALVE
VALVE OPERATING PRESSURE GAGE
ROTATION
FINISH
START
100
RACK & PINION ASSEMBLY
POWERS DIRECT ACTING THERMO-REGULATOR
REMOTE CONTROL CAM (ROTATES ONCE PER 24 HR)
CAM FOLLOWER
KILN WALL
STEAM SUPPLY LINE
THERMOSTATIC ROD
½" Φ POWERS DIAPHRAGM VALVE

FIGURE 5(a)

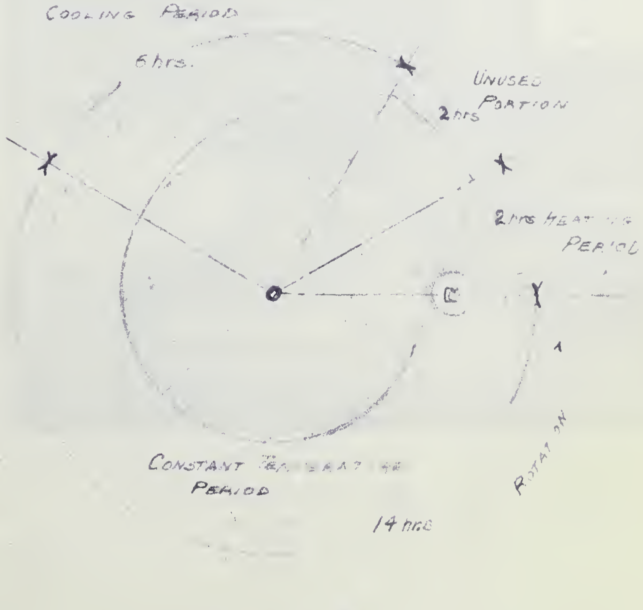


FIGURE 5(b)

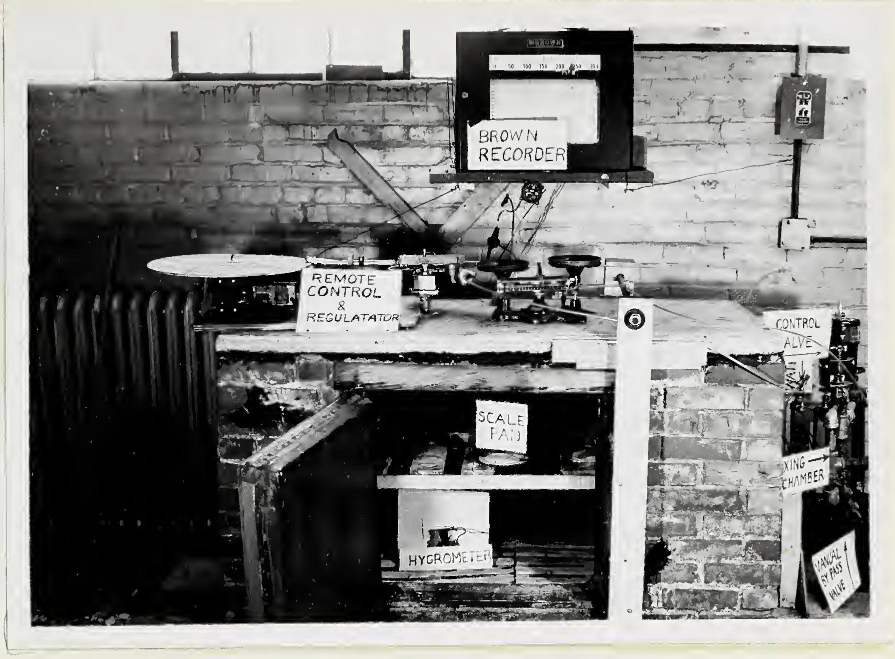


Fig. (6)(a) Front View of Kiln

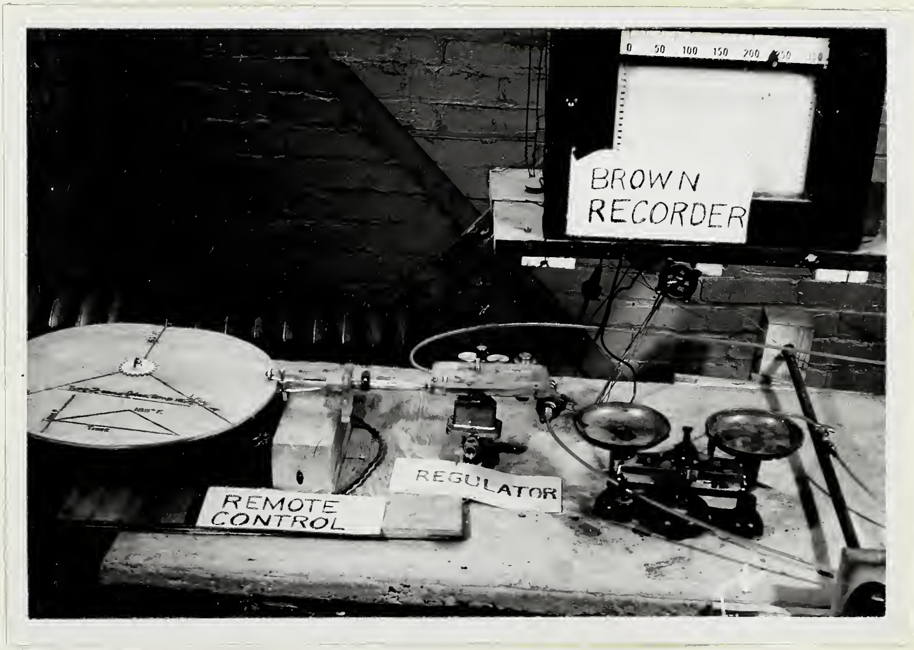


Fig. (6)(b) Top View of Kiln

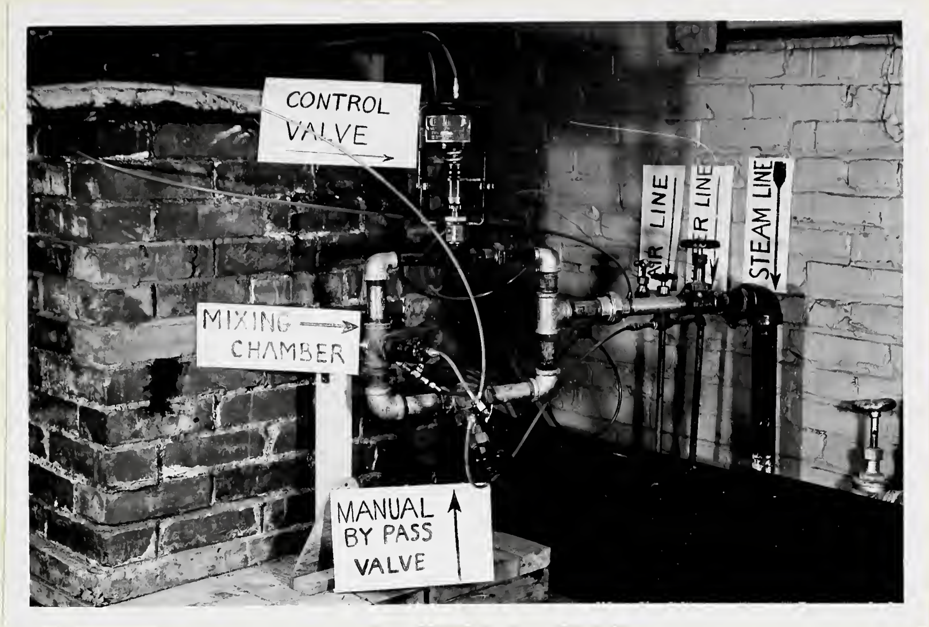


Fig. (7)(a) End View of Kiln

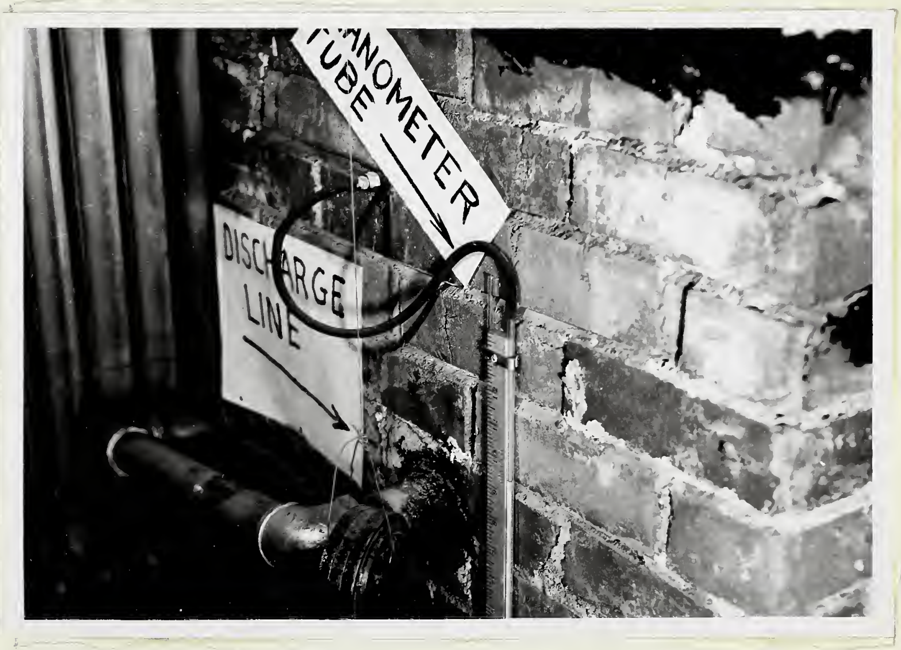


Fig. (7)(b) End View of Kiln

inch, so that for all practical purposes the kiln atmosphere was at atmospheric pressure.

To obtain the variations in weight of the concrete unit as the curing progressed a small beam type of balance was used. A scale pan was suspended inside the kiln by a wire running through a small hole in the roof of the ~~scales~~ kiln.

The relative humidity inside the kiln was measured by a thermocouple hygrometer. A flannel wick was wrapped around a thermocouple and the wick suspended in water and another thermocouple was placed just above the wet thermocouple. These two thermocouples indicated the wet and dry bulb temperatures within the kiln which could be used to compute the relative humidity. Enough space was left around the wick to allow a free circulation of air so the wet bulb temperature would be fairly accurate.

During the construction of the experimental curing kiln numerous trial runs were made to check the operation. These runs showed that the requirements as set down were fulfilled. The investigation into the effect of steam curing at atmospheric pressures upon concrete was then started.

II. Other Laboratory Equipment

(a). Mixer

The mixer used in this investigation was a $1\frac{1}{2}$-cubic foot Lancaster, type S.K.G. Serial No. 303, manufactured by Volta Manufacturing Company Limited of Welland, Ontario. It is powered by a 3-horse power Wagner

Electric Motor and is operated at a speed of 20 revolutions per minute. This mixer is designed for laboratory work, having an open, circular, removable type of drum in which the concrete is mixed. Vertical mixing blades rotate in an opposite direction to the drum and can be raised vertically to allow removal of the drum.

(b). Testing Machine

The load testing machine which was used for measuring compressive strengths of cylinders was a Baldwin Southwark Tate-Emery Testing Machine. It is a hydraulic, reaction-type load testing machine having a maximum capacity of 200,000 pounds. The machine has a pneumatic load indicator and also a loadpacer which enables the adjustment of the rate of loading to an desired number of pounds per second. The load indicator has three scales:

0 - 10,000 lbs.	Low Scale
0 - 50,000 lbs.	Medium Scale
0 -200,000 lbs.	High Scale

This allows for the choice of whichever scale is required to give the maximum deflection of the needle, thus enabling greater accuracy in reading. The machine was accurate to about 0.25 per cent.

(c). Concrete Molds

Cylindrical steel molds of 2, 4 and 6 inches inside diameter and 4, 8 and 12 inches high respectively were used. The walls of the molds were about one eighth of an inch thick. A steel base plate was provided for each mold. A clamping device was part of each cylinder to allow unloading of the

Fig. (8)(a) Testing Machine

Fig. (8)(b) - The three Cylinders on Testing Machine Platform.

mold. (See Figure (9), page (35)).

(d). Tamping Machines

Two types of tamping devices were used. The standard "Proctor" tamping device as used in soil investigations was used for the large and the medium sized cylinders. It was necessary to construct a smaller one to fit inside the 2 inch by 4 inch cylinder. The larger machine had a 5 - pound hammer and the smaller one a 3-pound hammer. In each case the hammer dropped one foot. A cylindrical guide was used in order that the hammer might be dropped one foot with each blow. (See Figures (b) and (10), Pages (35) and (36).)

(e). Moist Room

A cement plaster-lined room 10 feet by 10 feet by 8 feet was used as a moist room. Shelves and racks were provided in the moist room to hold the cylinders. A humidifier kept the room at a high relative humidity. The room was kept at a constant temperature of 70 degrees Fahrenheit by the use of the hot and cold water systems.

(f). Miscellaneous Equipment

Other equipment used included drying oven for moisture content samples, shovels, trowels, containers for moisture contents, scales, pails, equipment for capping cylinders, thermocouples, etc.

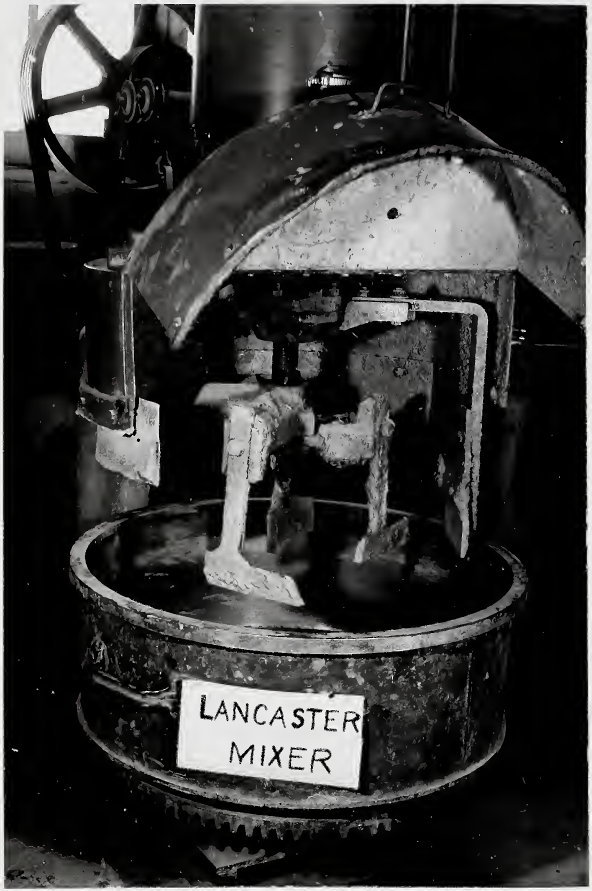


Figure 9 (a)

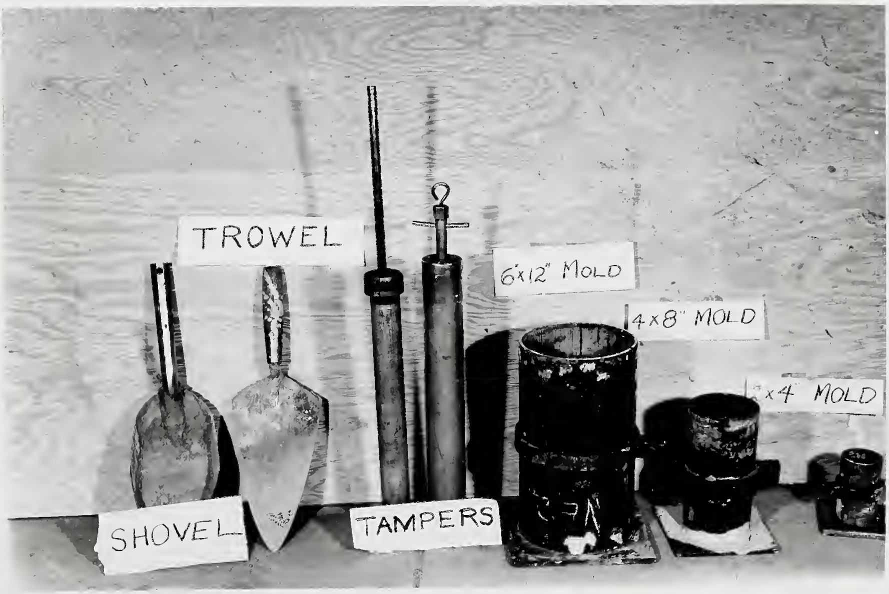
Lancaster

Mixer

Figure 9 (b)
(below)

Miscellaneous

Equipment



TAMPING MACHINES

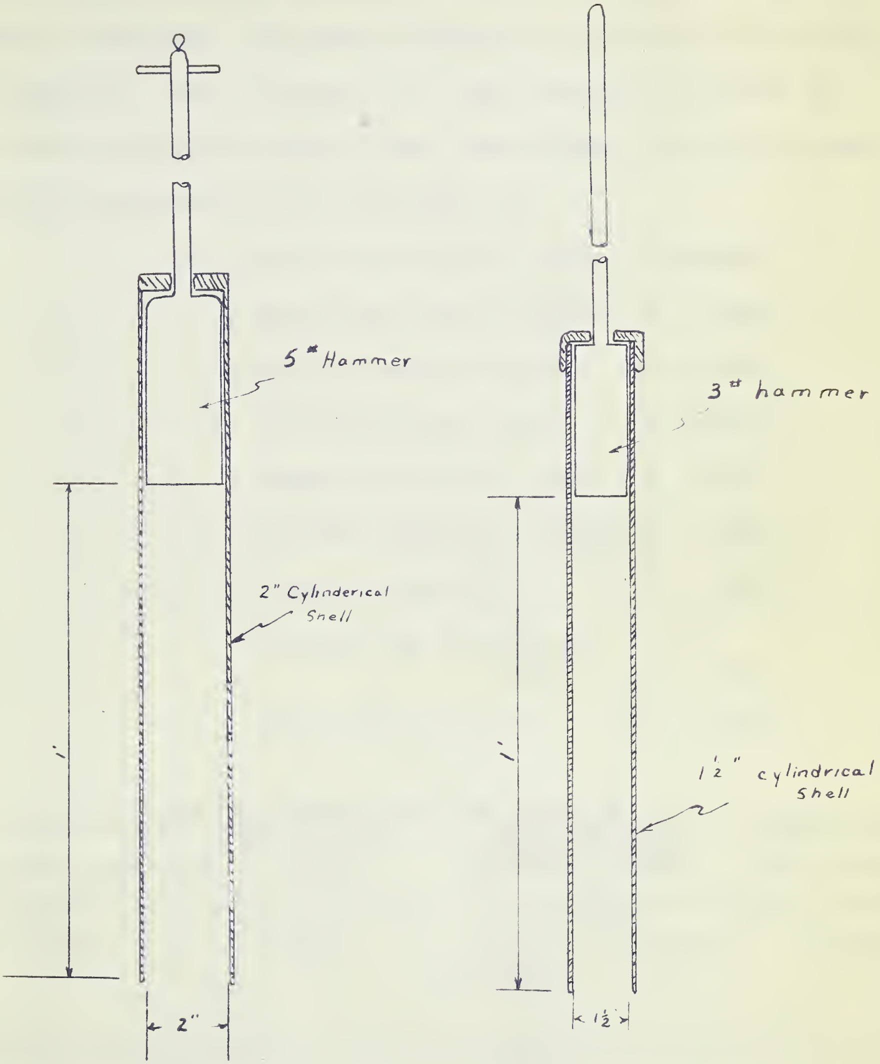


fig (10)

MATERIALS

Portland Cement

Standard Exshaw type I Portland Cement, produced by the Canada Cement Company Limited and supplied by Gorman's Limited, Edmonton, Alberta, was used in this investigation. The analysis for this cement as given in "Concrete Aggregate Evaluation and Effect of Surface and Finish on Resistance to Scaling" is:

Silicon Dioxide (SiO_2) = 22.01%

Aluminum Oxide ($\overset{Al_2}{A_{12}}O_3$) = 5.69%

Ferric Oxide (Fe_2O_3) = 2.95%

Calcium Oxide (CaO) = 63.21%

Magnesium Oxide (MgO) = 2.87%

Sulphur Trioxide (SO_3) = 2.07%

Loss on Ignition = 0.76%

Sodium and Potassium Oxide = 0.44%

Insoluble Residue = 0.45%

Physical Properties of Cements

Specific Gravity	Soundness Pats	Time of Set		Water for Consistency
		Initial	Final	
3.13	O.K.	2 hrs. 15 mins.	6 hrs.	26.6%

Note:

The above cement analysis was made two years ago so that the cement used in this investigation probably varied slightly from this analysis.

It was necessary to use two batches of the above cement in this investigation, the new batch being used after mix No. 10.

Aggregates

The fine aggregate used in this investigation was Elk Island pit run sand.

The coarse aggregate used was ½-inch gravel obtained from the Alberta Concrete Products.

An analysis of the aggregates follows:

Tests were run as outlined in the booklet, "A.S.T.M. Standards on Mineral Aggregates, Concrete and Nonbitumious Highway Materials", published by A.S.T.M. in September, 1948.

Physical Properties of Aggregates

Materials	Absorption (24 hr.) % by Wt.	Specific Gravity			Coal & Lignite % by Wt.	Color Test
		Bulk	Bulk (Sat.)	Apparent		
½" Coarse Aggregate	1.3	2.61	2.61	2.70	- -	- -
Sand	1.0	2.59	2.62	2.66	0.01	#2

Sieve Anaylsis of Elk Island Sand

Sieve Size	Wt. Retained	Per cent Retained	Cumulative % Retained
4	31.1	6.2	6.2
8	41.2	8.4	14.6
14	83.5	16.7	31.3
28	109.5	22.0	53.3
48	202.5	40.5	93.8
100	23.5	4.7	98.5
Pan	8.2	1.6	100.00

F.M. = 2.97

Sieve Anaylsis of ½-Inch Coarse Aggregate

Sieve Size	Wt. Retained	Per cent Retained	Cumulative % Retained
1"	0	0	0
½	1.74	6.1	6.1
3/8	5.35	18.9	29.9
4	15.40	54.0	78.9
8	1.68	5.9	84.9
14	0.71	2.5	87.3
28	0.57	2.0	89.3
48	1.85	6.5	95.8
100	0.56	2.1	97.9
Pan	0.56	2.1	100.0

Water

Water from the Edmonton Water System was used.

LABORATORY PROCEDURE

Outline

Three types of curing cycles, run at three different maximum temperatures, were used in this investigation. In the first type of cycle the kiln was heated to temperature at a fairly rapid rate (about one degree Fahrenheit per minute) then this temperature was held constant for about sixteen hours; after this the kiln temperature was brought back to room temperature at a fairly slow rate of temperature fall (about ½ degree Fahrenheit per minute). This cycle was run at maximum temperature of 135 degrees Fahrenheit, 150 degrees Fahrenheit and 185 degrees Fahrenheit.

For the second type of cycle the kiln temperature was brought slowly up to the peak temperature and then slowly brought back to room temperature. The rate of temperature rise and temperature fall were the same. The curing cycle lasted for approximately twenty-four hours. The cycle was run at temperatures of 135 degrees, 160 degrees and 185 degrees Fahrenheit maximum temperatures.

In the third type of cycle the kiln temperature was raised fairly rapidly (about one degree Fahrenheit per minute) to an intermediate temperature 20 degrees Fahrenheit below the peak temperature. The kiln temperature was then raised very slowly to the peak temperature. When the peak temperature had been reached the kiln was cooled off slowly to room temperature. This cycle was run at peak tem-

peratures of 135 degrees, 160 degrees and 185 degrees Fahrenheit.

It was thought that by using these three cycles some information could be gained concerning the best type of curing cycle and the best temperature for steam curing of concrete at atmospheric pressures. Moreover, the effect of steam curing upon the crushing strength of concrete might be brought out more readily.

In a previous section it was stated that the size of the concrete specimen might have some effect upon the final result. It was therefore decided to use three sizes of cylinders in this investigation, namely 2 inch by 4 inch, 4 inch by 8 inch, and 6 inch by 12 inch cylinders. The three sizes of cylinders were fabricated from the same mix and then subjected to the same curing conditions.

To gain information on what happens to the concrete cylinders when subjected to different curing conditions after steam curing, cylinders were made for moist curing after steam curing and for curing in the laboratory air. From each concrete mix twelve cylinders were made, 4 small, 4 medium and 4 large. One cylinder of each of three sizes was put directly into the moist room, to be broken after 7 days and to be used as a control. The remaining nine cylinders were steam cured; three (one of each size) were broken immediately after the steam curing cycle was complete; three (one of each size) were moist cured for six days then put in the laboratory air for seven days and then broken;

three (one of each size) were left in the laboratory air for thirteen days after steam curing and then broken.

To gain some information on how steam curing affects the moisture content of the concrete, moisture contents of all the cylinders were taken. A total of 276 cylinders was made and tested.

Mix Design

After a search through the bibliography it was decided to use a 1:6 mix (1 part cement and 6 parts aggregate) and a water cement ratio of 0.45. For sand and gravel aggregates this was the most common mix design used by investigators in the literature. The sand and ½-inch gravel were combined in equal amounts, which resulted in a well graded aggregate. When the mix had been made from this design, the batch weights for a two hundred pound mix were computed: water - 12.08 pounds, cement - 26.84 pounds, sand - 80.54 pounds and gravel 80.54 pounds. The weights for the aggregates were based on the saturated surface dry basis. A trial mix was run and found to be very satisfactory. The mix was very dry and had to be tamped into the molds **thus** bringing in another problem.

Tamping

The amount of tamping a concrete cylinder is given will affect the final value for the compressive strength. Because of this it was decided to give each unit volume of concrete the same compactive effort. That is each cubic inch of concrete received the same amount of energy in the

process of being compacted in the cylinders. Two types of tamping machines were used: one with a 5-pound hammer falling one foot, used for the large and medium sized cylinders, and one with a 3-pound hammer falling one foot, for the smaller cylinders. For each unit volume of concrete to receive the same compactive effort, the large cylinders were compacted in eight layers, each layer being subjected to 22 blows, the medium cylinders in 5 layers, each layer receiving 10 blows, and the small cylinders in 3 layers, the first two layers receiving 3 blows and the last layer receiving 4 blows. This procedure proved very tedious but was strictly adhered to throughout the investigation.

Preparation of Aggregates

To make possible the production of mixes which were very close to the design mix, it was necessary to prepare the aggregate. This preparation consisted of mixing the aggregate thoroughly with water until uniform conditions had been obtained and the moisture content had passed the saturated surface dry condition. Each size of aggregate was then put in individual containers and covered with a damp sack, and samples of the prepared aggregates were then taken for moisture content computations. This procedure made it feasible to gain good control over the mix.

Fabrication

To eliminate as many errors as possible in the fabrication, the same sequence of events was followed for each mix. All the materials of the mix were weighed to the

nearest ounce and then everything was put in the mixer except the water. The materials were mixed dry for one minute and then the water was put into the mixer and the mixing continued for another five minutes. At the same time samples of the aggregate were taken to make moisture content computations in order to know the exact condition of the aggregate as it went into the mixer.

When the mixing was finished the concrete was tamped into the molds. When thermocouples were required, they were located at the centre of the cylinder. The test cylinders were then left to stand for about 4 hours before being stripped and put into the steam kiln and the moist room.

Loading the Steam Kiln

Extreme care had to be used in loading the kiln as the concrete had not quite set up, with the result that it was easy to chip off the edges of the cylinders. The cylinders were spaced in an orderly arrangement in the kiln. The thermocouples were the connected to the Brown Recorder. One of the specimens was placed on the scale pan in order to obtain the weight variations as the curing cycle progressed.

The kiln was now prepared for the curing cycle. The proper cam was placed on the electric motor and the necessary adjustment made. The fog nozzles had to be cleaned every day as heat seemed to precipitate a substance which clogged up the small screen within the fog nozzles. The electric motor was started and the steam, air and water

turned on. When the steaming cycle was complete the doors were opened and 3 cylinders were tested, 3 put in the moist room and 3 left in the laboratory air.

Testing Procedure

The cylinders were capped with a sulfur and fire-clay mixture to ensure a square and level surface. The cross sectional diameter of each cylinder was taken. All cylinders were tested in the testing machine at constant rates of loading for each size. The load was applied at 40,000 pounds per minute for the large cylinders, 20,000 pounds per minute for the medium cylinders and 4,000 pounds per minute for the small cylinders. Immediately after the cylinders were broken, a sample of concrete was taken from each for moisture content computations.

The results of the tests are tabulated in Tables (1) and (2), Page (50) and (51).

Tables and Graphs of Results

Table No. 1

Table No. 1 shows the weight variations in the medium cylinder during the curing cycle. See Graph numbers (14), (18), (19) and (20) for the relationship between these weight variations and the various curing cycles. The weight variations include the water that condensed upon the outside of the cylinder and upon the scale pan.

Table No. 2

This shows the compressive strengths and the moisture content of all the cylinders tested. It also shows the water cement ratio and batch weights of the twenty-two mixes.

Table No. 3

Table No. 3 lists the strengths of all the cylinders broken, as per centages.

First the strengths are expressed as per centages of the strengths of the large cylinder after it was cured in the moist room for 7 days. That is, the strength of the large cylinder after seven days moist curing is taken as 100 per cent. Per centage values were used to eliminate partially the effect of the variations arising between the different mixes.

Next, the strengths are expressed as a per centage of the strength of the corresponding cylinder size, using adjusted values for the seven day moist cured strengths. When all the moist cured strength values found for the three cylinder sizes were used, on the average the small cylinder

showed a strength value of 71 per cent of the large cylinder and the medium cylinders showed a strength value of 104 per cent of the large cylinder. These three values were used in computing the adjusted values found in Tables No. 3. For example in Mix No. 8:

Compressive strengths of the large, small and medium cylinders were 2770, 1970 and 2970 psi, the average value being 2570 psi. This value was then taken as 91.67 per cent of the strength of the large cylinder (since the average value of 100 plus 71 plus 104 is 91.67).

Then the adjusted strength value for the large cylinder is:

$$\frac{100 \times 2570}{91.67} = 2800 \text{ psi}$$

For the small cylinder:

$$0.71 \times 2800 = 1990 \text{ psi}$$

For the medium cylinder:

$$1.04 \times 2800 = 2910 \text{ psi}$$

If the strength value for the small cylinder did not compare favorably with the strength of the other two cylinders, it was ignored in the computations of the adjusted values as in Mix No. 6.

Compressive strength of the large, small and medium cylinder were 2859, 1020 and 2360; the average of 2850 plus 2360 is 2605.

Then the adjusted value for the large cylinder is:

$$2605 \times \frac{100}{102} = 2560 \text{ psi}$$

For the small cylinder:

2560 X 71 = 1820 psi

For the medium cylinder:

2560 X 104 = 2660 psi

These adjustments were made in order to obtain a better value for the concrete strength, especially for the small cylinders. The values for the other two cylinders did not change greatly.

Table No. 4

Table No. 4 gives the mean values for the different curing cycles as computed from Table No. 3.

Table No. 5

Table No. 5 gives the mean values for the moisture contents as obtained from Table No. 2. The table also gives the strength gain in per cent of the cylinders that were moist cured and air cured after steaming over cylinders that were broken immediately after steam curing. Values were obtained by computations from Table No. 4. Strength gain values were computed in the following manner: From Cycle No. 1 at 135 degrees Fahrenheit, Table No. 4; strength value for large cylinder steam cured then broken is 73 per cent and the value for large cylinder steam cured, then moist cured for 6 days and cured in laboratory air for 7 days is 133 per cent; therefore gain = (133 - 73) per cent = 60 per cent. The table gives only the strength gain values for the per centage based on the large cylinder.

Graphs

Graphs No. 1 to No. 12 are plotted from the values in Table No. 4.

Graphs No. 13 to No. 21 are graphs of the various steaming cycles. They show the temperature of the kiln air and temperature of the large, small and medium sized cylinders during the curing cycle. The temperatures were taken at the centres of the cylinders.

Graph No. 22 shows the temperature variations to which mixes No. 10 and 11 were subjected. These two cycles were not run intentionally but were due to a break down in the equipment supplying the air to the kiln and regulator valve.

Graph No. 23 is a plot of the water cement ratio vs. the compressive strength. Graph No. 24 is a plot of the moisture contents vs. the compressive strengths.

Table No. 1

Weight Variations During Curing

Weight Variations in Grams	Watch Time	Date	Weight Variations in Grams	Watch Time	Date
Mix No. 2					
Curing Cycle No. 1 at 160' F.			Mix No. 17		
			Curing Cycle No. III at 135'		
0	3:00 P.M.	Jan. 17	0	2:30 P.M.	Feb.22
+ 7	3:15 P.M.		17	3:20 P.M.	
+ 20	5:05 P.M.		25	3:40 P.M.	
+ 28	8:00 A.M.	Jan. 18	25	4:10 P.M.	
+ 20	9:00 A.M.		28	5:10 P.M.	
+ 4	10:20 A.M.		27	8:30 A.M.	Feb.24
0	10:55 A.M.		19	8:45 A.M.	
- 8	12:00 A.M.		15	9:15 A.M.	
			11	9:55 A.M.	
			10	10:30 A.M.	
Mix No. 4			10	11:00 A.M.	
Curing Cycle No. 1 at 160' F.			8	11:30 A.M.	
0	3:00 P.M.	Jan. 19			
25	4:15 P.M.				
26	8:15 A.M.	Jan. 20	Mix No. 19		
19	8:40 A.M.		Curing Cycle No. III at 160'F.		
9	9:15 A.M.				
4	9:35 A.M.		0	3:15 P.M.	Feb.23
- 7	10:45 A.M.		15	3:35 P.M.	
- 15	12:00 A.M.		25	4:45 P.M.	
			24	5:05 P.M.	
			24	5:30 P.M.	
Mix No. 8			25	8:05 A.M.	Feb.24
Curing Cycle No. 11 at 185' F.			20	8:55 A.M.	
			17	9:30 A.M.	
0	3:00 P.M.	Jan. 26	17	10:30 A.M.	
23	4:00 P.M.				
23	5:30 P.M.				
12	9:00 A.M.	Jan. 27			
4	11:00 A.M.				

Table No 2

Mix No.	1	3	2	4	5	6	12	21	22	9	10	16	7	8	17	18	15	19	20	13	14	11	Averages Across
Cycle	135	135	160	160	185	185	135	135	135	160	160	160	185	185	115 135	115 135	140 160	140 160	140 160	165 185	165 185	135 [illegible] 200 140	
Water Cement Ratio	0.447	0.455	0.463	0.448	0.457	0.446	0.445	0.448	0.448	0.463	0.442	0.425	0.425	0.450	0.443	0.443	0.433	0.438	0.438	0.452	0.451	0.442	
WEIGHTS (in POUNDS), OF MATERIALS AS PUT IN THE MIXER (Weights of Aggregates on Saturated Surface Dry Basis)																							
Water	12.01	12.21	12.43	12.00	12.29	11.97	11.97	12.01	12.01	12.48	11.86	11.35	11.40	12.08	11.88	11.88	11.63	11.71	11.71	12.14	12.11	11.86	
Cement	26.84	26.84	26.84	26.84	26.84	26.84	26.84	26.84	26.84	26.84	26.84	26.84	26.84	26.84	26.84	26.84	26.84	26.84	26.84	26.84	26.84	26.84	
Sand	80.46	80.40	80.27	80.50	80.42	80.72	80.87	80.85	80.80	79.12	81.15	82.14	80.07	80.52	81.03	81.03	80.27	80.40	80.40	80.59	80.60	80.70	
½" Gravel	80.69	80.53	80.42	80.49	80.42	81.23	80.65	80.33	80.31	80.70	80.11	79.63	80.65	80.52	80.21	80.21	81.22	81.01	81.01	80.39	80.31	80.56	
COMPRESSIVE STRENGTHS OF CYLINDERS CURED IN MOIST ROOM FOR 7 DAYS (psi)																							
Large	2520	3420	2260	3415	3320	2850	3620	3940	4060	3300	3420	4080	3100	2770	3740	3920	4080	4010	3820	3620	3690	3740	
Small	2630	2380	1400	2960	2390	1020	3440	* 2380	* 2700	2450	2120	* 2910	2210	1970	* 2600	* 2620	3540	* 2540	* 2720	2020	2910	2780	
Medium	2870	3230	2190	3620	3730	2360	3730	3980	4070	3480	3420	3870	3030	2970	4050	4800	4630	4050	4110	3670	3870	3760	
COMPRESSIVE STRENGTH OF CYLINDERS STEAM CURED AND BROKEN 24 HOURS AFTER CASTING (psi)																							
Large	1700	2710	1720	2690	2310	1905	2310	2620	2670	2380	2690	2330	2105	1905	2780	2730	2640	3440	3360	2730	2830	2540	
Small	1780	1940	1170	1950	1910	1660	2110	1740	1990	1830	2880	2000	1940	1960	2280	2300	1960	1910	2360	2230	2360	1920	
Medium	1705	2730	1960	3260	2440	2130	2630	2610	2620	2400	2900	2850	2600	2210	3020	3510	2800	3420	3810	3230	3030	2710	
COMPRESSIVE STRENGTH OF CYLINDERS STEAM CURED THEN MOIST CURED FOR 6 DAYS THEN CURED FOR 7 DAYS IN LAB. AIR. psi)																							
Large	3200	4760	3240	4530	3790	2770	4820	4900	4830	3880	4060	4780	4050	3510	4600	5100	4500	5000	4860	3730	4030	3650	
Small	3390	3340	2170	3980	2100	1770	4300	2990	3420	3710	5230	4370	3070	3630	4050	4380	3380	2600	3340	3950	3280	3000	
Medium	3980	4370	3300	4480	4110	3100	5340	4700	5650	4700	4130	5700	4190	4300	5470	5800	5600	5400	4630	4590	4470	3900	
COMPRESSIVE STRENGTH OF CYLINDERS STEAM CURED THEN CURED IN LAB. AIR FOR 13 DAYS (psi)																							
Large	3140	4640	2730	4170	3620	3150	4710	4750	4560	3640	3780	4500	3630	3290	4430	5020	4200	4500	4560	3940	3980	3390	
Small	3320	2790	1950	3520	3300	2120	3420	2540	3680	2760	3720	2780	3050	2930	3500	3340	2800	3500	3500	3520	2890	3270	
Medium	3540	4625	3280	4770	4150	3150	4850	4540	5260	3900	4460	4460	3900	3660	5370	5850	4880	5100	5180	4530	4460	3820	
MOISTURE CONTENTS OF CYLINDERS CURED IN MOIST ROOM FOR 7 DAYS (ON BASIS OF DRY WEIGHT)%																							
Large	5.31	5.00	5.52	—	4.80	4.15	4.28	5.02	4.63	3.95	5.85	4.94	4.14	5.86	4.34	3.93	5.01	4.29	4.05	4.81	4.50	4.52	4.77
Small	5.19	5.04	4.66	—	4.82	3.90	4.65	3.66	4.41	4.02	4.77	3.81	4.74	5.37	4.37	4.63	4.71	3.25	4.35	4.33	3.96	4.36	4.37
Medium	5.18	4.82	4.83	—	4.50	4.02	4.65	4.46	4.87	4.35	5.03	4.85	4.54	5.69	4.61	4.66	4.85	4.68	3.92	5.04	4.82	3.99	4.74
MOISTURE CONTENTS OF CYLINDERS STEAM CURED AND BROKEN AFTER 24 HOURS (ON BASIS OF DRY WEIGHT) %.																							
Large	4.25	5.16	5.33	5.22	5.03	5.10	4.85	4.94	4.58	4.64	4.97	5.32	4.98	5.28	5.25	5.[illegible]3	3.40	4.65	5.04	5.08	5.12	3.85	4.92
Small	4.74	5.35	5.67	5.00	3.33	3.53	4.30	3.22	4.39	4.64	2.91	3.73	3.27	3.73	3.75	3.72	2.72	2.22	3.23	3.46	2.81	2.78	3.55
Medium	5.11	5.05	4.22	3.83	4.83	4.59	4.91	4.74	3.97	4.41	3.28	4.18	4.40	5.63	4.58	4.73	3.94	3.94	4.63	3.84	4.76	3.30	4.49
MOISTURE CONTENTS OF CYLINDERS STEAM CURED THEN MOIST CURED FOR 6 DAYS THEN CURED FOR 7 DAYS IN LAB. AIR. (on Basis of Dry Weight) %																							
Large	5.74	3.78	3.04	3.74	3.00	2.16	4.38	3.87	3.52	3.16	3.28	3.92	2.78	2.62	4.70	4.16	3.88	3.94	3.32	2.31	2.94	2.61	3.59
Small	2.07	2.28	1.30	1.79	1.27	1.26	1.47	2.00	1.58	1.63	2.19	1.94	1.36	2.46	2.11	2.01	2.21	1.72	1.96	1.95	1.52	1.28	1.71
Medium	3.33	3.20	2.48	2.66	1.40	1.68	3.80	3.23	3.51	2.70	1.98	3.41	2.24	2.22	4.06	3.09	2.79	2.61	2.79	2.15	2.45	1.68	2.71
MOISTURE CONTENTS OF CYLINDERS STEAM CURED THEN CURED IN LAB. AIR FOR 13 DAYS (on Basis of Dry Weight) %																							
Large	3.65	2.65	1.98	2.88	1.42	1.27	3.94	3.42	3.26	2.34	1.90	2.89	2.41	3.01	3.84	2.77	2.45	2.82	1.96	2.99	3.06	1.75	2.69
Small	1.18	1.43	0.93	1.18	0.78	0.64	1.33	1.22	1.25	1.27	1.15	1.16	0.94	1.03	1.27	1.24	1.36	1.21	1.14	0.88	1.07	0.77	1.10
Medium	2.01	2.14	1.95	2.16	1.56	1.06	2.87	2.63	2.06	1.74	1.95	2.26	2.44	1.31	2.25	2.70	2.62	2.81	2.43	~	1.86	1.21	2.08

* Average of 3 cylinders

Table No 3

Mix No	1	3	2	4	5	6	12	21	22	9	10	16	7	8	17	18	15	19	20	13	14	11	Averages Across
Cycle	135	135	160	160	185	185	135	135	135	160	160	160	185	185	115 135	115 135	140 160	140 160	140 160	165 185	165 185	[illegible]	
STRENGTHS As % of LARGE CYLINDER AFTER 7 DAYS MOIST CURING																							
For Cylinders Moist Cured for 7 days																							
Large	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Small	104	70	62	87	72	36	95	61	66	74	62	71	71	71	70	67	87	64	71	56	79	74	71
Medium	114	95	97	106	112	83	103	101	100	105	100	95	98	106	108	122	113	101	107	101	105	101	104
For Cylinders Broken 24 hrs. After Casting																							
Large	67	79	76	79	70	67	64	66	68	72	79	57	68	69	75	70	60	86	88	75	77	68	72
Small	71	57	52	57	57	58	58	44	49	55	84	49	63	71	61	59	48	48	62	62	64	51	59
Medium	68	80	87	96	74	75	70	66	65	73	85	70	84	80	81	90	69	85	99	89	82	73	80
For Cylinders Steam Cured, Moist Cured for 6 days and Cured in Lab Air for 7 days																							
Large	127	139	143	133	114	97	133	124	119	116	118	117	131	127	123	130	110	125	127	103	109	98	121
Small	135	98	96	117	63	62	119	76	84	112	153	107	99	131	108	112	83	65	87	109	89	80	104
Medium	158	128	146	131	124	109	147	119	139	142	121	140	135	156	146	148	137	134	121	127	121	104	134
For Cylinders Steam Cured and Cured for 13 days in Lab. Air																							
Large	125	136	121	122	109	111	130	120	112	109	110	110	117	119	118	128	103	112	119	109	108	91	116
Small	132	82	86	103	99	74	95	65	91	84	109	68	98	106	94	85	69	87	92	97	78	87	91
Medium	141	135	144	140	125	111	134	115	130	118	130	109	126	132	143	149	120	127	135	125	121	102	128
STRENGTHS as % of CORRESPONDING CYLINDER SIZE AFTER 7 DAYS MOIST CURING USING ADJUSTED 7 DAY STRENGTHS																							
Adjusted 7 day Strengths																							
Large	2640	3285	2130	3450	3440	2560	3600	3880	3970	2990	3360	3950	3035	2800	3780	4110	4270	3950	3870	3380	3420	3740	
Small	1875	2340	1510	2450	2440	1820	2560	2750	2820	2120	2380	2800	2210	1990	2680	2920	3030	2800	2750	2400	2430	2650	
Medium	2750	2415	2210	3590	3670	2660	3750	4030	4130	3110	3490	4110	3160	2910	3830	4280	4440	4110	4030	3515	3560	2890	
For Cylinders Steam Cured and Broken 24 hours After Casting																							
Large	65	82	81	78	67	74	64	68	67	80	80	59	69	68	73	67	58	87	87	81	83	68	74
Small	95	83	77	80	78	91	82	63	71	86	121	71	88	102	85	79	65	68	86	93	97	72	81
Medium	62	80	89	91	68	80	67	65	64	77	83	69	82	76	79	82	63	83	95	92	86	94	78
For Cylinders Steam Cured, Moist Cured for 6 days and Cured in Lab Air for 7 days																							
Large	121	145	152	131	110	108	134	126	122	130	120	121	133	127	122	124	105	126	125	110	118	98	123
Small	180	142	144	162	86	91	168	109	121	175	220	156	139	182	150	150	112	93	121	165	135	113	141
Medium	145	128	149	125	115	117	142	116	137	151	118	139	132	148	143	136	126	131	116	130	125	135	132
For Cylinders Steam Cured and Cured 13 Days in Lab Air																							
Large	119	141	128	121	105	123	131	122	115	122	113	114	120	117	117	122	98	114	118	116	116	91	118
Small	178	119	129	144	135	116	134	92	130	177	156	99	138	147	130	114	93	125	127	147	119	123	133
Medium	129	135	148	133	116	118	130	113	127	125	128	109	123	125	140	137	110	124	129	129	125	132	125
STRENGTHS as % of CORRESPONDING CYLINDER SIZE AFTER 7 DAYS MOIST CURING USING ACTUAL 7 DAY STRENGTHS																							
For Cylinders Steam Cured and Broken 24 hours After Casting																							
Large	68	79	76	79	70	67	64	66	68	72	79	57	68	69	75	70	60	86	88	75	77	68	72
Small	68	81	84	66	80	162	62	73	74	75	136	69	88	99	88	88	55	75	87	110	81	69	81
Medium	60	84	89	90	65	90	68	66	65	69	85	74	86	75	75	73	60	84	93	88	78	72	77
For Cylinders Steam Cured and Moist Cured 6 days and Cured in Lab Air for 7 days																							
Large	127	139	143	133	114	97	133	124	119	116	118	117	131	127	123	130	110	125	127	103	109	98	121
Small	129	140	155	135	88	174	125	125	127	151	247	150	139	184	156	167	95	102	123	195	112	108	139
Medium	138	135	150	123	110	132	143	118	139	135	120	148	138	145	135	121	121	133	113	125	115	104	129
For Cylinders Steam Cured and Cured in Lab Air For 13 Days																							
Large	125	136	121	122	109	111	130	120	112	109	110	110	117	119	118	128	103	112	119	109	108	91	116
Small	126	117	140	119	138	207	100	107	136	112	175	96	138	149	135	128	79	138	129	175	99	117	127
Medium	123	143	150	132	111	133	130	114	129	[illegible]	130	115	129	123	133	122	105	126	126	123	115	102	125

MEAN VALUES

Table No 4

Cycle	135	165	185	135	160	185	115 135	140 160	165 185
STRENGTH AS % OF LARGE CYLINDER									
	Cylinders Steam Cured and Broken 24 hours After Casting								
Large	73	78	69	66	69	69	73	78	76
Small	64	55	57	51	63	67	60	53	63
Medium	74	91	74	67	76	82	85	84	85
	Cylinders Steam Cured, 6 Days Moist Cured, 7 days Lab. Air								
Large	133	138	105	125	117	129	127	121	106
Small	116	106	62	93	123	115	110	77	99
Medium	143	138	116	135	134	145	147	131	124
	Cylinders Steam Cured and Cured in Lab Air for 13 days								
Large	131	122	110	121	110	118	123	111	109
Small	112	95	86	84	87	102	90	83	87
Medium	138	142	118	126	119	129	146	124	123
STRENGTH AS % OF CORRESPONDING CYLINDER SIZE (ADJUSTED)									
	Cylinders Steam Cured and Broken 24 hours After Casting								
Large	73	80	70	66	80	69	70	87	82
Small	89	79	84	72	92	94	82	73	95
Medium	72	90	74	65	76	80	80	80	88
	Cylinders Steam Cured, 6 Days Moist Cured, 7 Days Lab Air								
Large	133	141	109	128	123	130	123	119	114
Small	161	153	91	133	165	160	150	109	150
Medium	137	137	116	132	136	140	140	124	127
	Cylinders Steam Cured and Cured in Lab for 13 Days								
Large	130	125	114	123	116	120	120	116	116
Small	148	136	125	119	144	142	122	126	133
Medium	132	140	117	123	120	124	139	121	127
STRENGTH AS % OF CORRESPONDING CYLINDER SIZE (ACTUAL)									
	Cylinders Steam Cured and Broken 24 hours After Casting								
Large	73	78	69	66	69	69	73	78	76
Small	74	75	121	70	72	93	88	72	81
Medium	72	85	78	66	76	80	74	79	95
	Cylinders Steam Cured, 6 Days Moist Cured 7 Days Lab. Air								
Large	133	138	105	125	117	129	126	119	106
Small	134	145	131	126	150	161	160	103	153
Medium	136	136	122	133	134	141	128	122	120
	Cylinders Steam Cured and cured 13 Days in Lab. Air								
Large	131	122	110	121	110	118	123	111	109
Small	122	129	172	114	124	143	131	133	137
Medium	133	141	122	124	119	126	128	119	119

Moisture Content Averages

Table No. 5

Cycle	135°	160	185	135	160	185	115 135 135	140 165 160 185	185 185
	7 Day Moist								
Large	5.15	5.52	4.47	4.64	4.91	5.00	4.13	4.45	4.65
Small	5.11	4.66	4.36	4.24	3.15	5.05	4.50	4.10	4.14
Medium	5.00	4.83	4.26	4.66	4.74	5.11	4.63	4.48	4.93
	24 Hour Steam Curing								
Large	4.70	5.27	5.06	4.75	4.74	5.13	5.19	4.36	5.10
Small	5.04	5.38	3.43	3.97	3.76	3.50	3.73	2.72	3.13
Medium	5.08	4.03	4.71	4.54	3.95	5.01	4.65	4.17	4.30
	24 Hour Steam Curing ≠ 6 Days Moist Curing ≠ 7 Days Lab. Air								
Large	3.76	3.39	2.58	3.92	5.18	2.70	4.43	3.71	2.62
Small	2.17	1.54	1.26	1.85	1.92	1.91	2.06	1.96	1.73
Medium	3.26	2.57	1.54	3.51	2.69	2.23	3.57	2.73	2.30
	24 Hour Steam Curing ≠ 13 Days Curing in the Lab. Air								
Large	3.15	2.43	1.34	3.54	2.37	2.71	3.30	2.41	3.02
Small	1.30	1.05	0.71	1.26	1.19	0.98	1.25	1.23	0.97
Medium	2.07	2.05	1.31	2.52	1.98	1.87	2.47	2.62	1.86

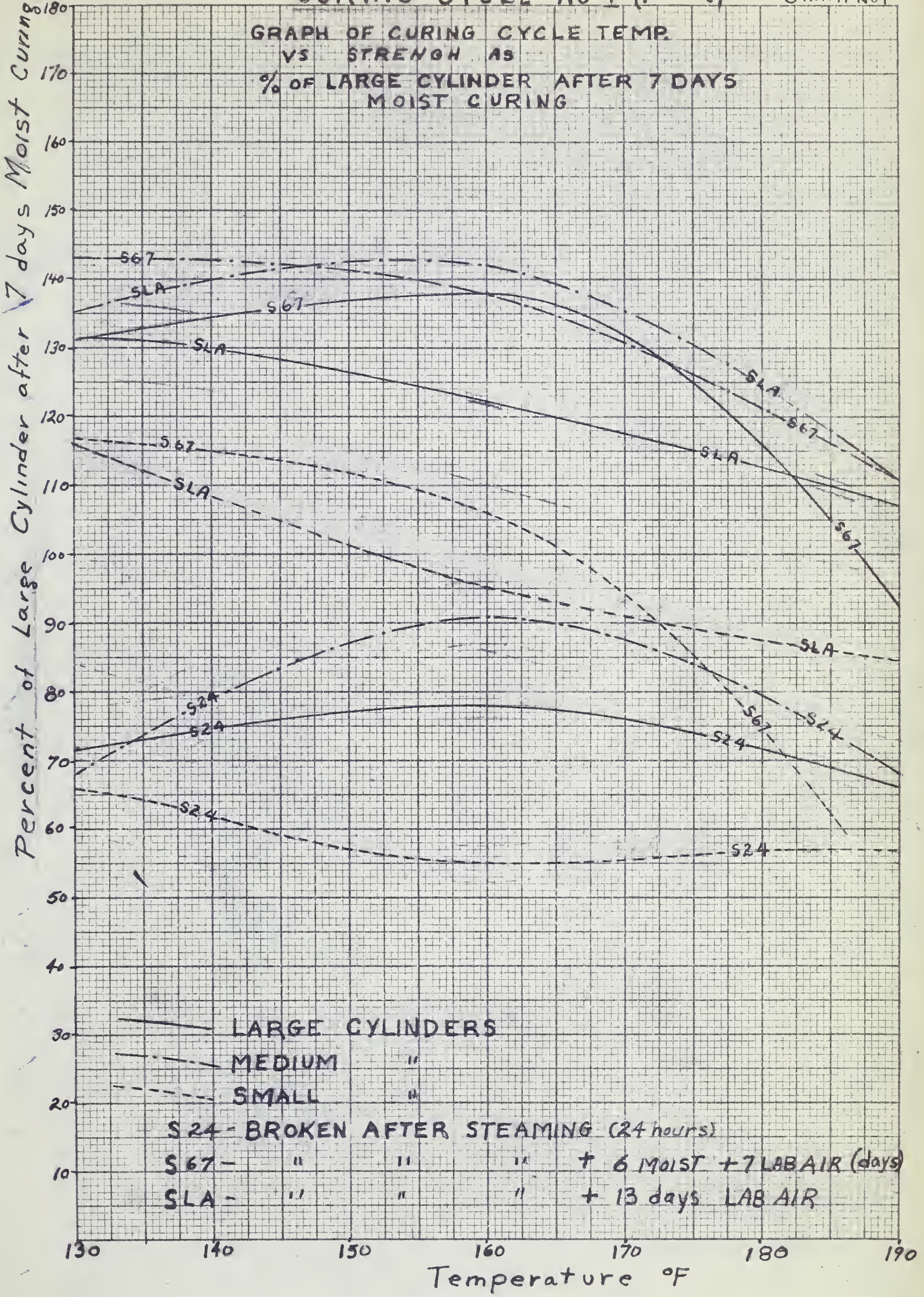
Strength Gain of Cylinders Moist Cured and Air Cured After Steam Curing

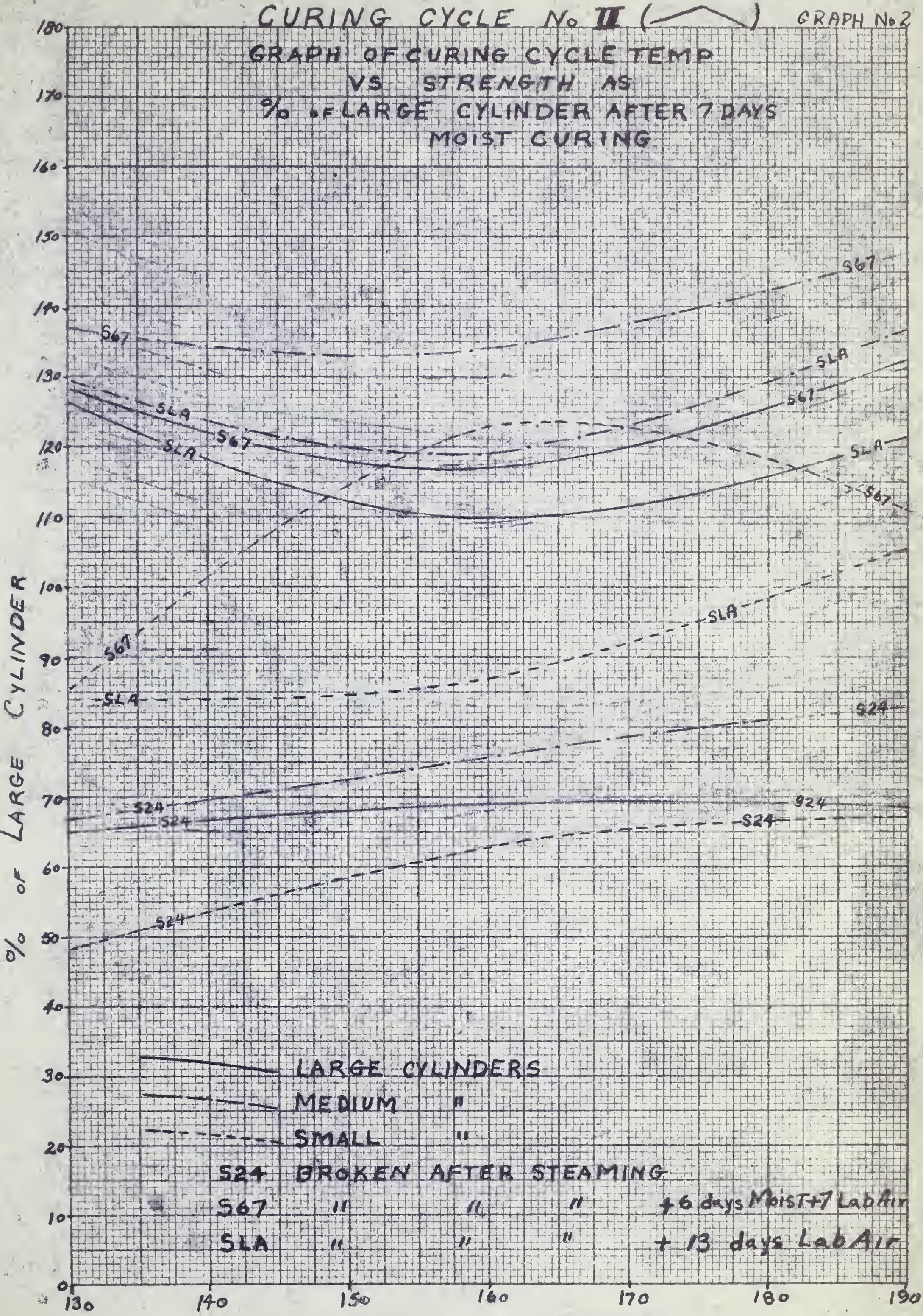
	24 Hour Steam Curing ≠ 6 Days Moist Curing ≠ 7 Days Lab. Air								
Large	60	60	36	59	48	60	54	43	30
Small	52	51	5	42	60	48	50	24	36
Medium	69	47	42	68	58	63	62	47	39
	24 Hour Steam Curing ≠ 13 Days Curing in the Lab. Air								
Large	58	44	41	55	41	49	50	33	33
Small	48	40	29	33	24	35	30	30	24
Medium	64	51	44	59	43	47	61	40	38

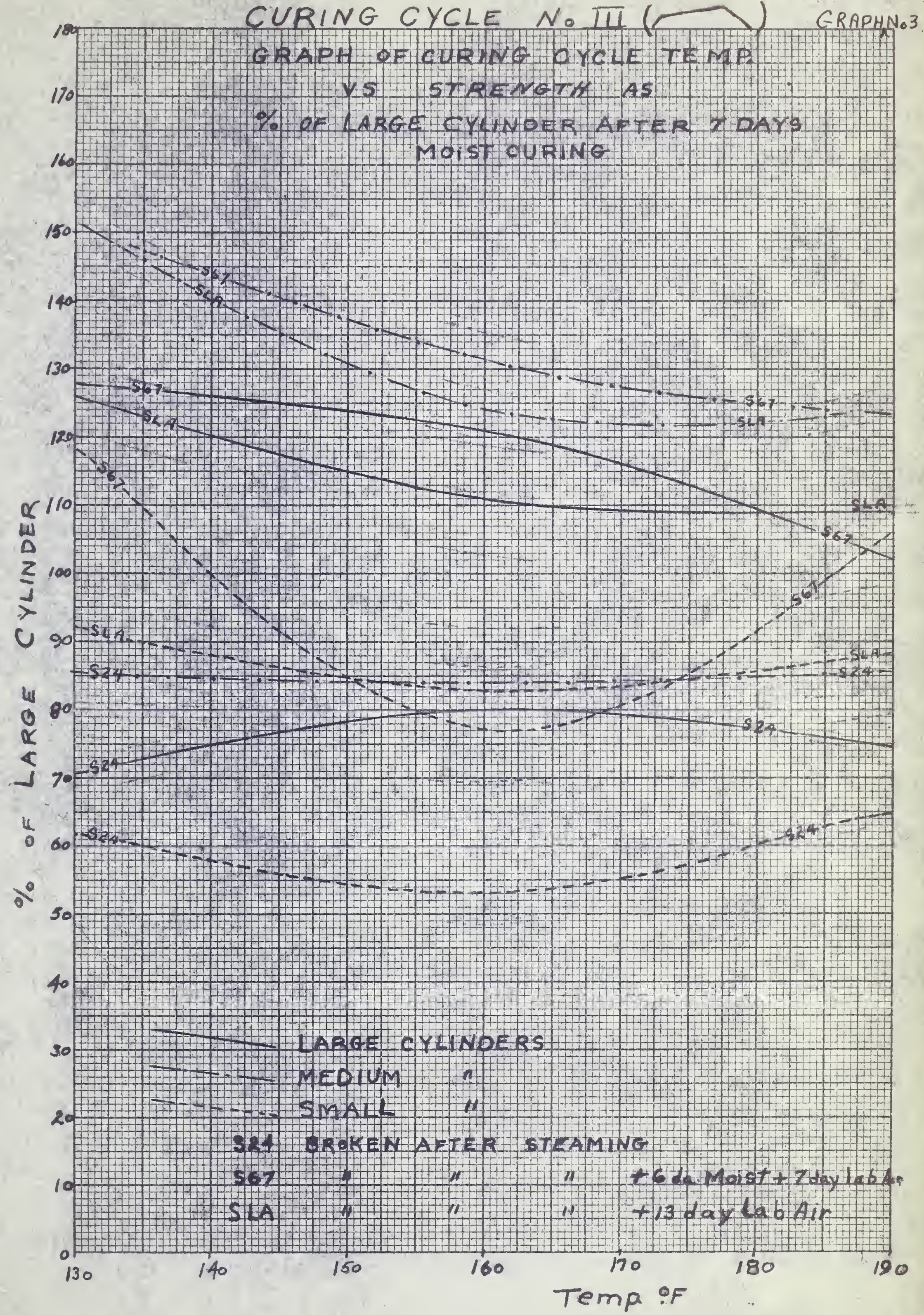
132
170
182
132
170
182
132
170
182

CURING CYCLE No I

GRAPH No 1




CURING CYCLE No II
GRAPH No 2
GRAPH OF CURING CYCLE TEMP
VS STRENGTH AS
% OF LARGE CYLINDER AFTER 7 DAYS
MOIST CURING
% OF LARGE CYLINDER
Temp. °F
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
130
140
150
160
170
180
190
S67
SLA
S67
SLA
S67
SLA
S67
SLA
S67
SLA
S67
SLA
S24
S24
S24
S24
S24
S24
LARGE CYLINDERS
MEDIUM "
SMALL "
S24 BROKEN AFTER STEAMING
S67 " " " + 6 days Moist + 7 Lab Air
SLA " " " + 13 days Lab Air

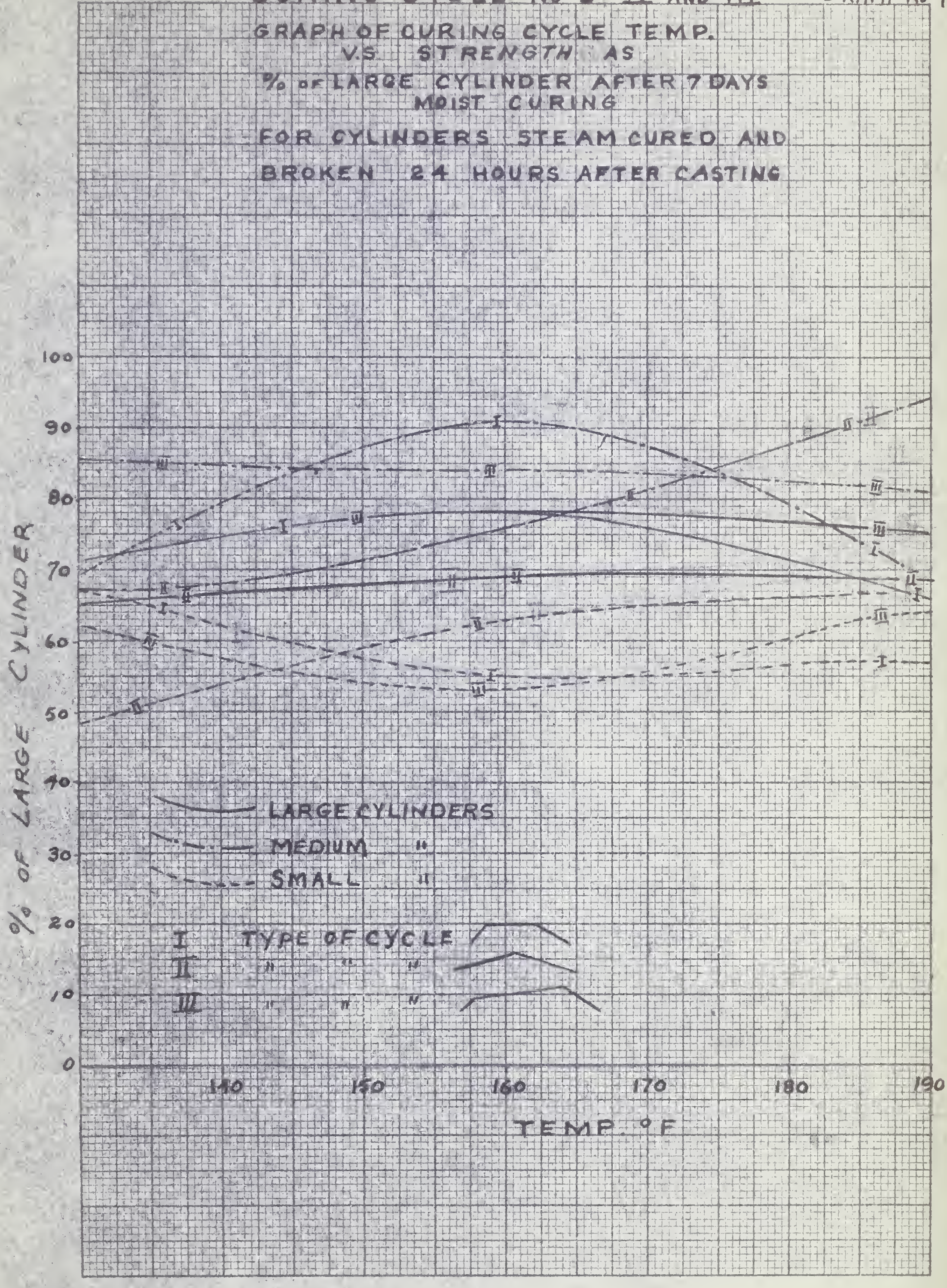


CURING CYCLE No III

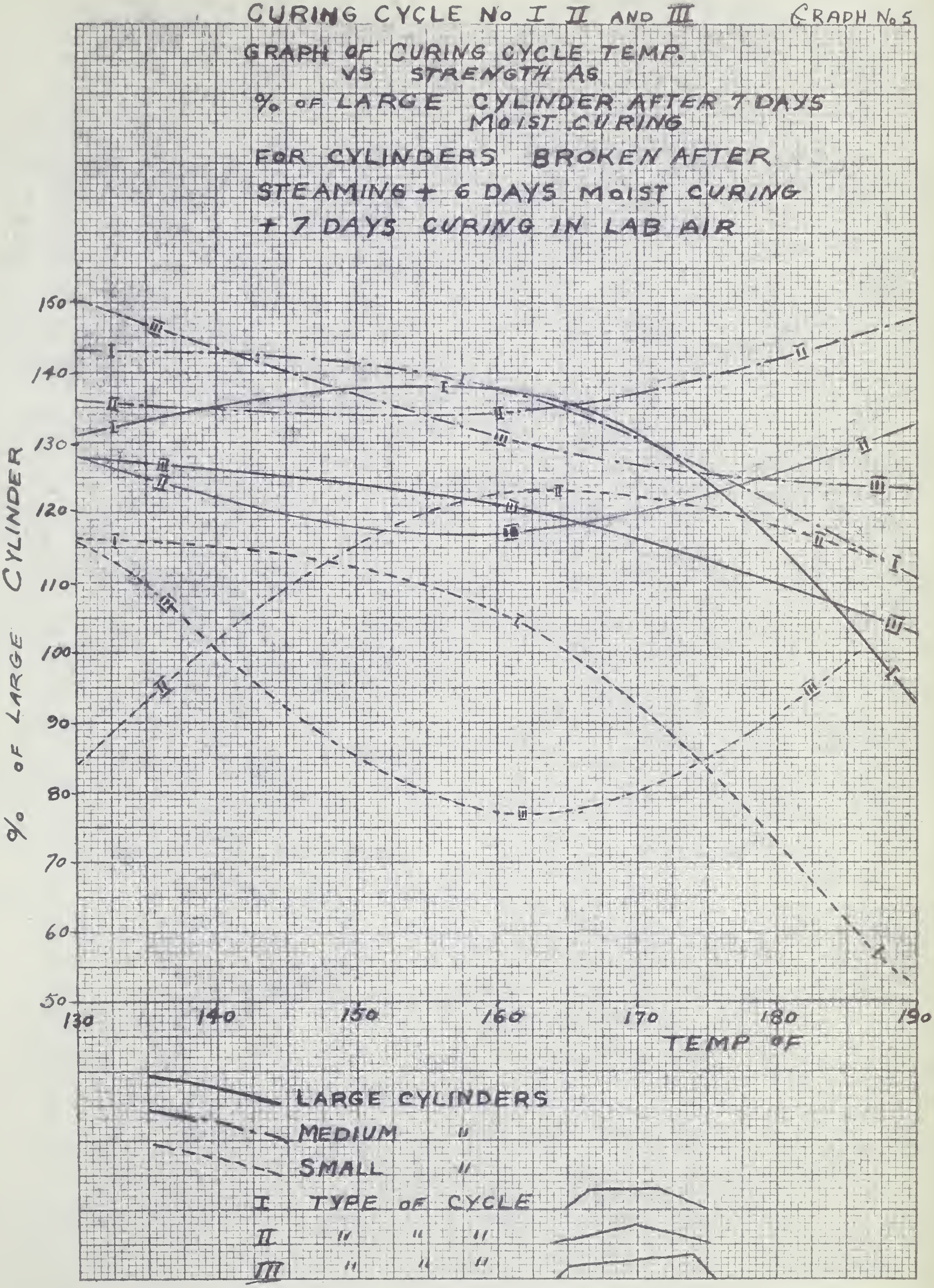
GRAPH No.3

GRAPH OF CURING CYCLE TEMP.
VS STRENGTH AS
% OF LARGE CYLINDER AFTER 7 DAYS
MOIST CURING

CURING CYCLE No I II AND III GRAPH No. 4



CURING CYCLE No I II AND III GRAPH No 5



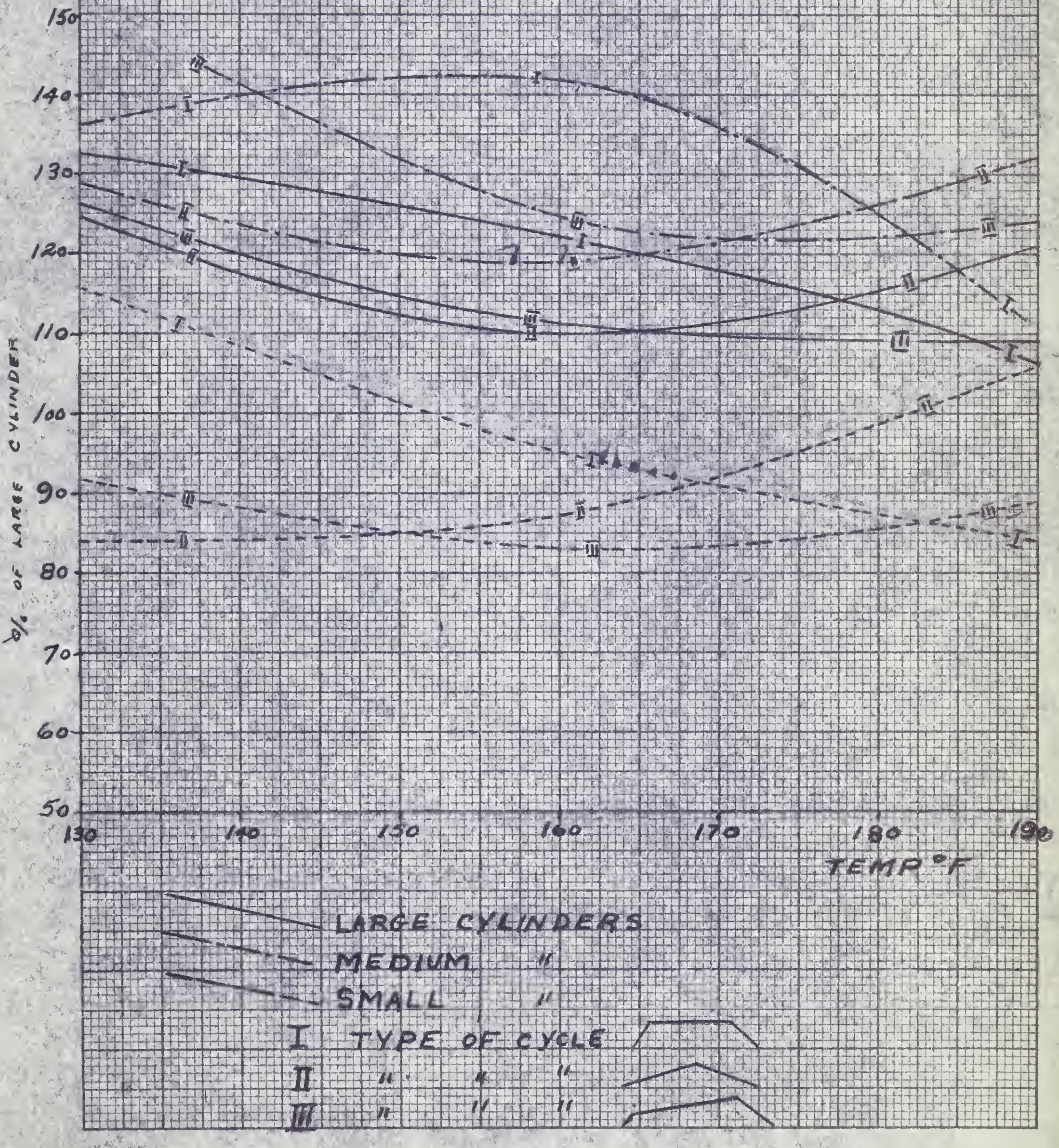
GRAPH OF CURING CYCLE TEMP.
VS STRENGTH AS
% OF LARGE CYLINDER AFTER 7 DAYS MOIST CURING

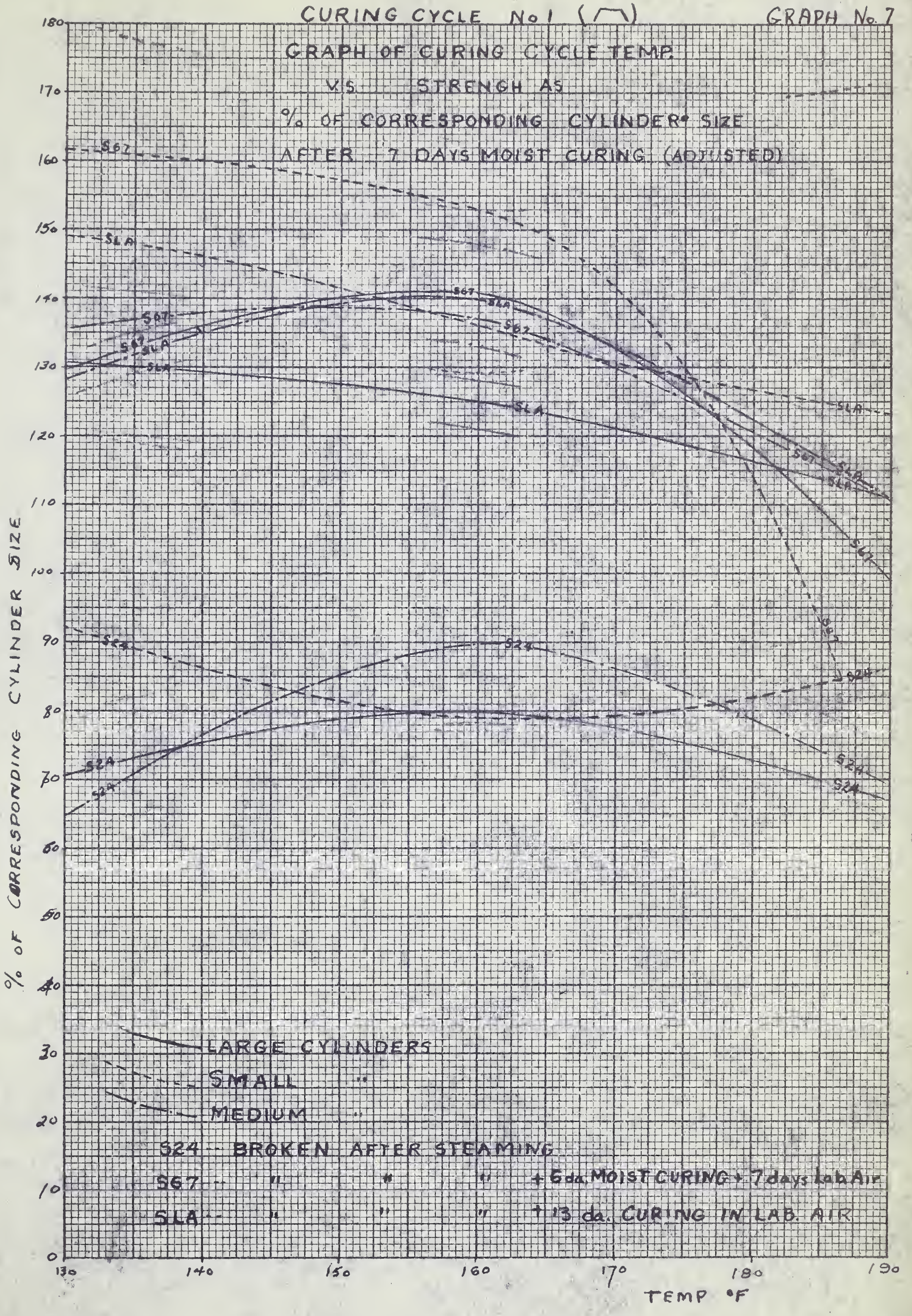
FOR CYLINDERS BROKEN AFTER
STEAMING + 6 DAYS MOIST CURING
+ 7 DAYS CURING IN LAB AIR

CURING CYCLE No I II AND III

GRAPH No 6

GRAPH OF CURING CYCLE TEMP
VS STRENGH AS
% OF LARGE CYLINDER AFTER 7 DAYS
MOIST CURING
FOR CYLINDERS BROKEN AFTER
STEAMING + 13 DAYS CURING
IN LAB AIR

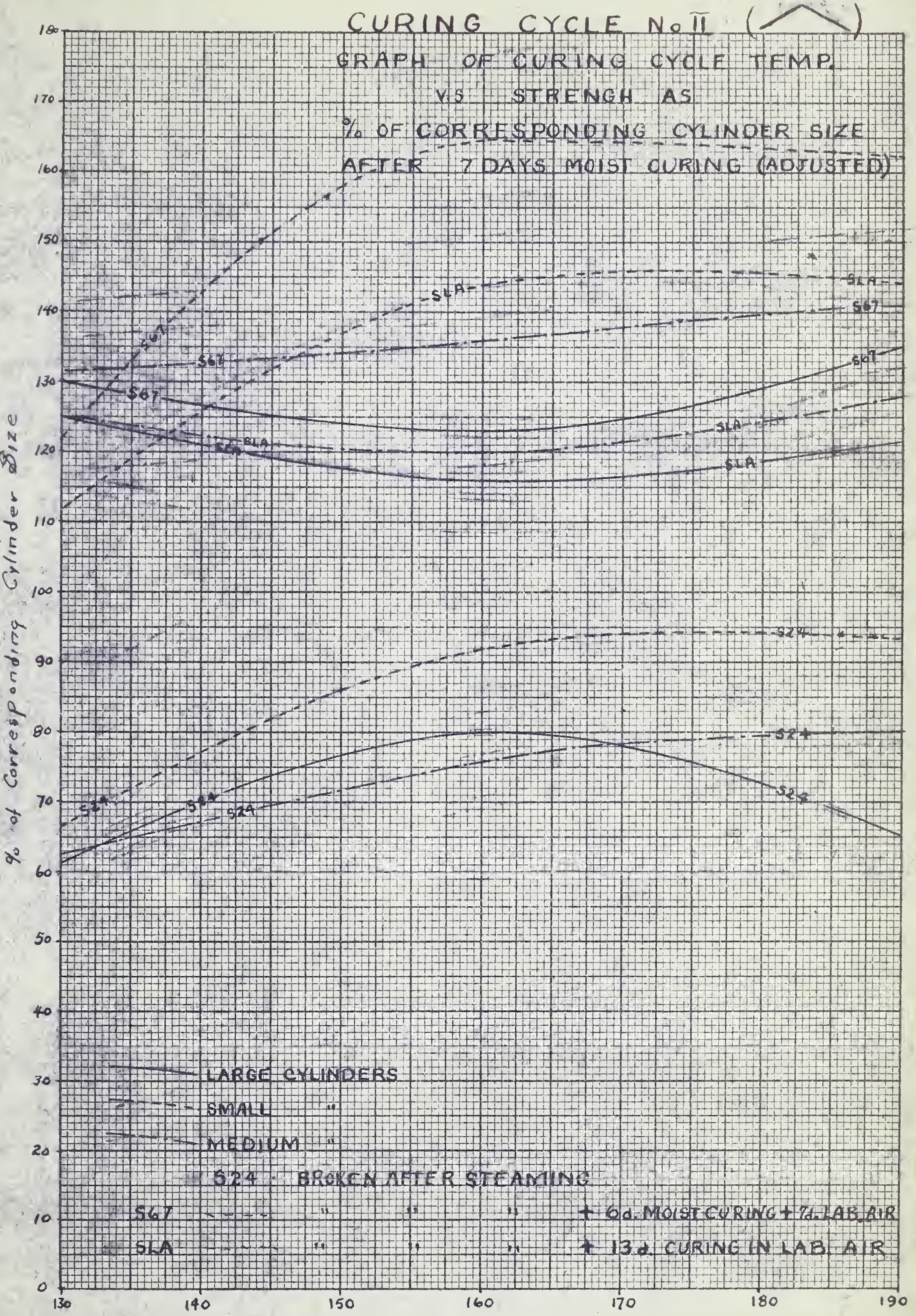




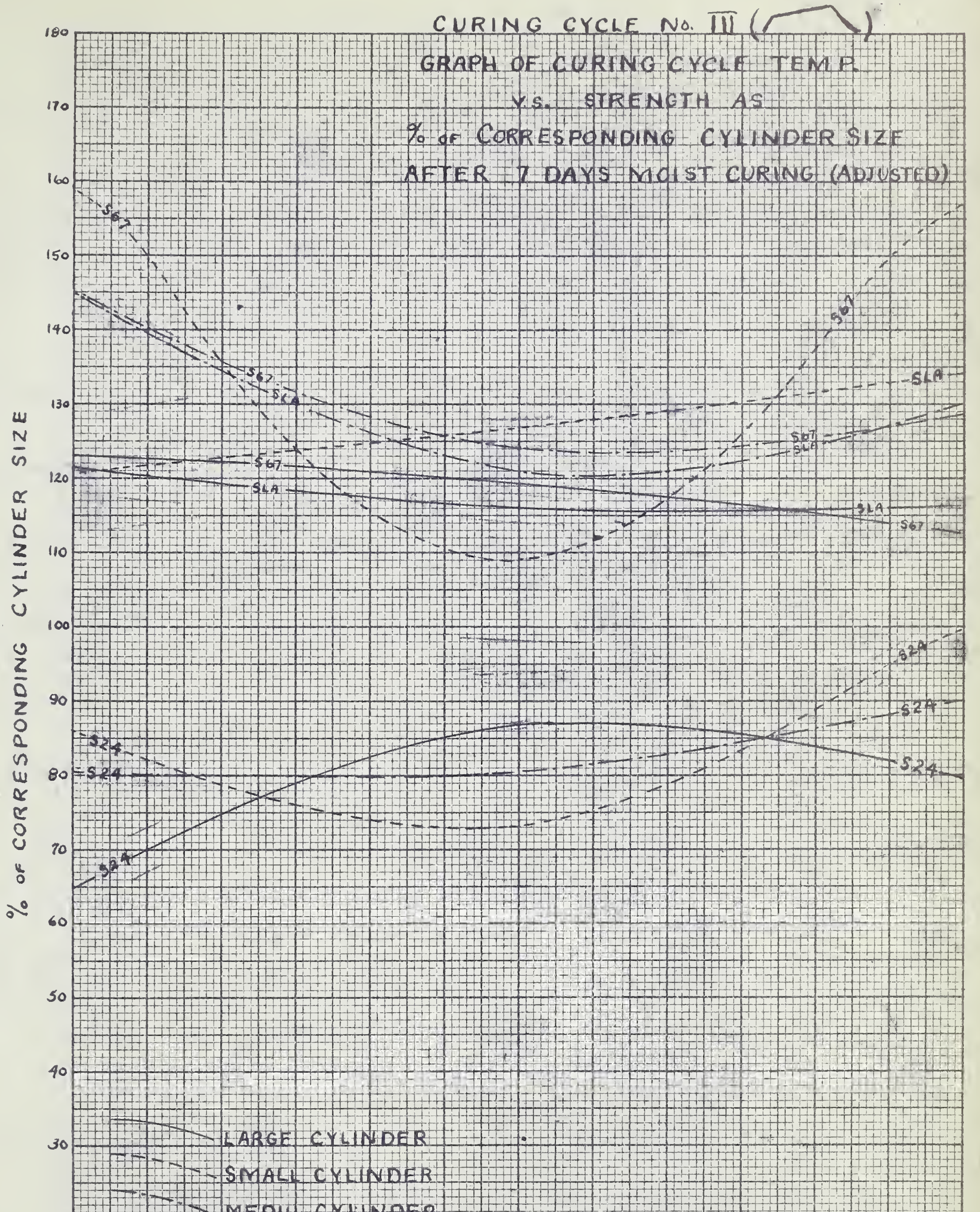
CURING CYCLE No 1 (⌒\) GRAPH No. 7

GRAPH OF CURING CYCLE TEMP. V.S. STRENGH AS % OF CORRESPONDING CYLINDER SIZE AFTER 7 DAYS MOIST CURING (ADJUSTED)

GRAPH No 8

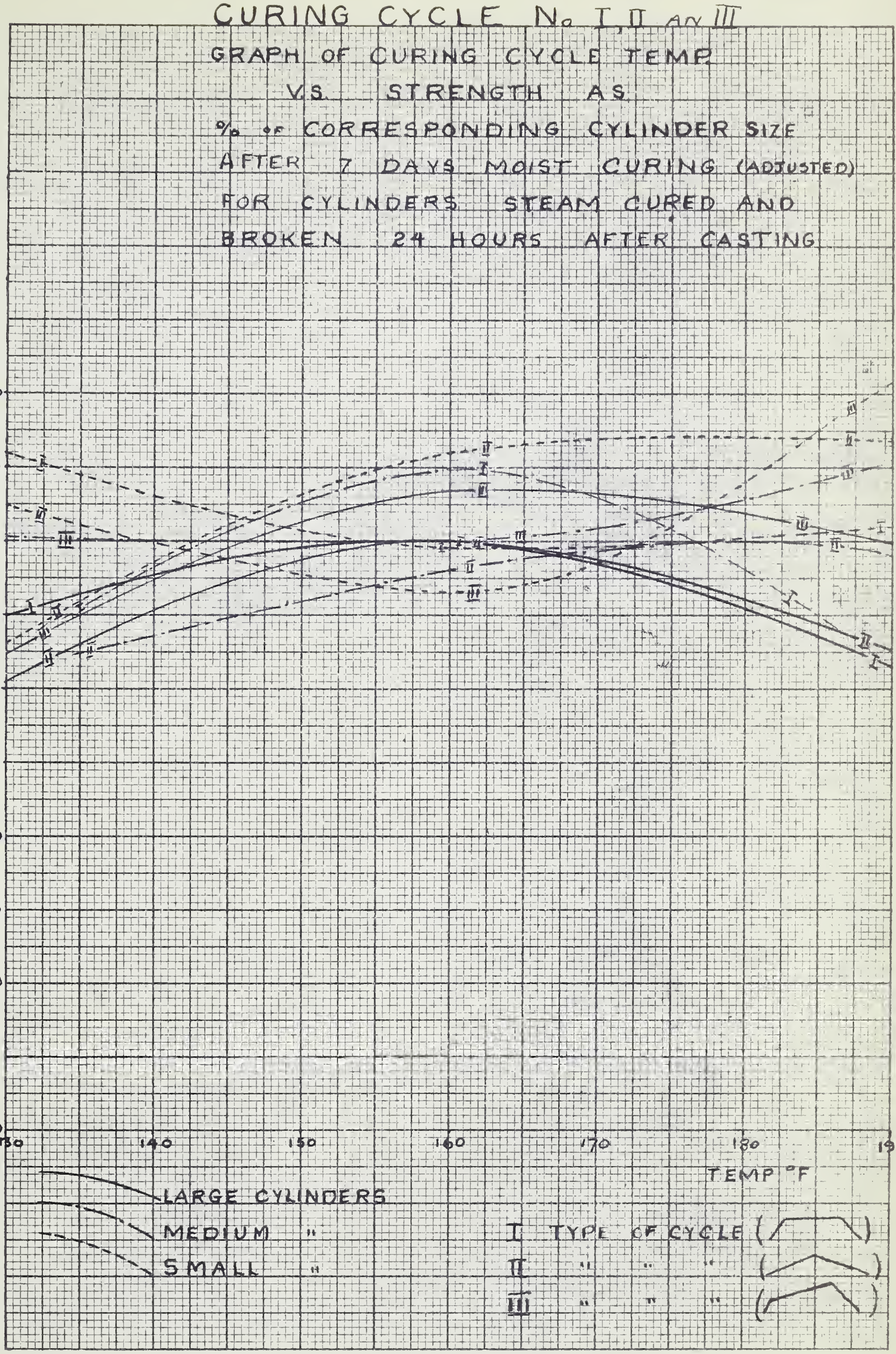

CURING CYCLE No II
GRAPH OF CURING CYCLE TEMP.
VS STRENGH AS
% OF CORRESPONDING CYLINDER SIZE
AFTER 7 DAYS MOIST CURING (ADJUSTED)
% of Corresponding Cylinder Size
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
130
140
150
160
170
180
190
S67
SLA
S24
LARGE CYLINDERS
SMALL "
MEDIUM "
S24 BROKEN AFTER STEAMING
S67 " " " + 6d. MOIST CURING + 7d. LAB. AIR
SLA " " " + 13 d. CURING IN LAB. AIR

GRAPH No 9


CURING CYCLE No. III
GRAPH OF CURING CYCLE TEMP.
v.s. STRENGTH AS
% of CORRESPONDING CYLINDER SIZE
AFTER 7 DAYS MOIST CURING (ADJUSTED)
% of CORRESPONDING CYLINDER SIZE
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
130
140
150
160
170
180
190
S67
SLA
S24
LARGE CYLINDER
SMALL CYLINDER
MEDIU CYLINDER
S24 --- BROKEN AFTER STEAMING
S67 -- " " " + 6d. MOIST CURING + 7d. LAB AIR
SLA -- " " " + 13 d. CURING IN LAB AIR

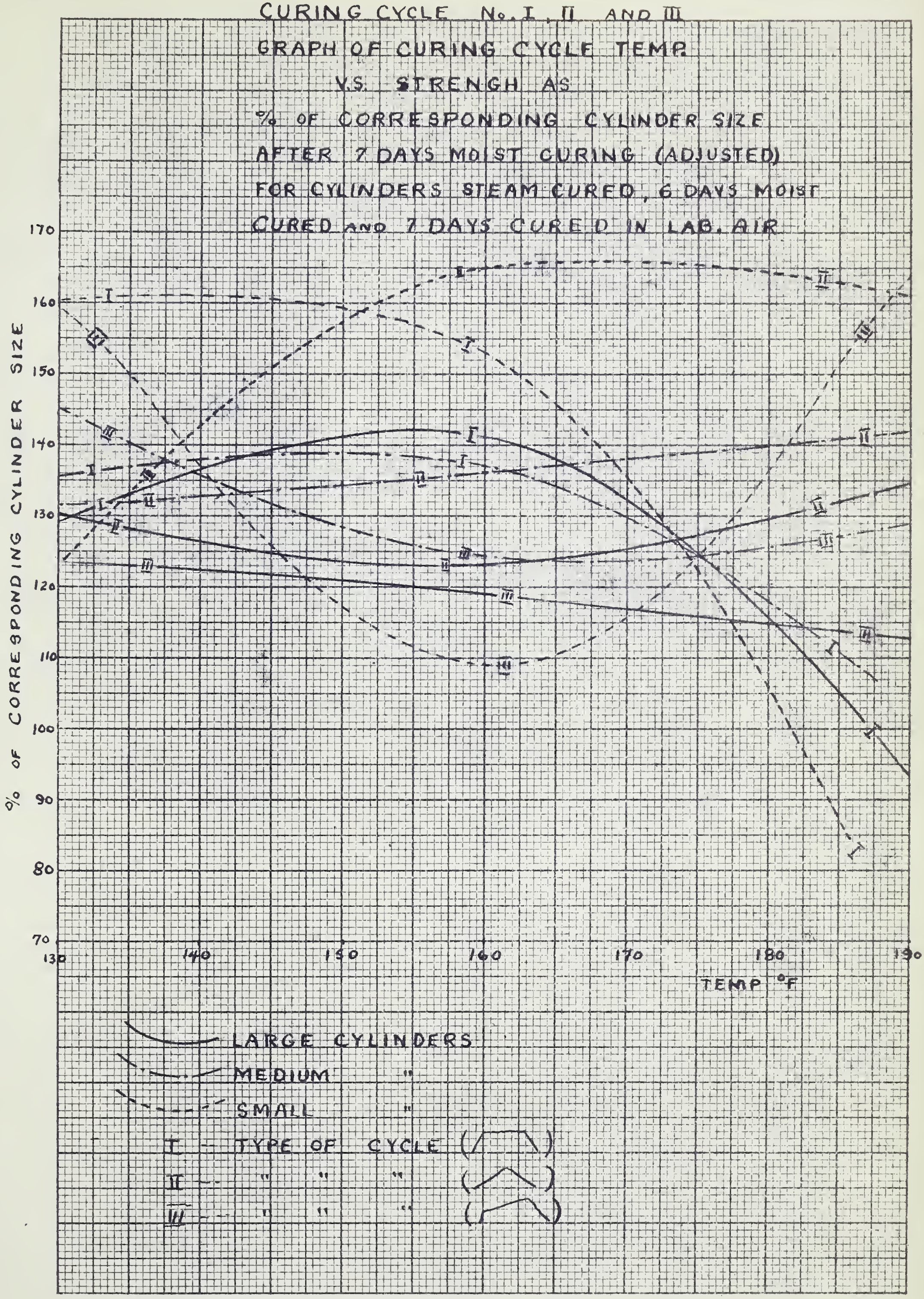
GRAPH No 10

CURING CYCLE No I, II AN III



GRAPH OF CURING CYCLE TEMP.
VS STRENGTH AS
% of CORRESPONDING CYLINDER SIZE
AFTER 7 DAYS MOIST CURING (ADJUSTED)
FOR CYLINDERS STEAM CURED AND
BROKEN 24 HOURS AFTER CASTING

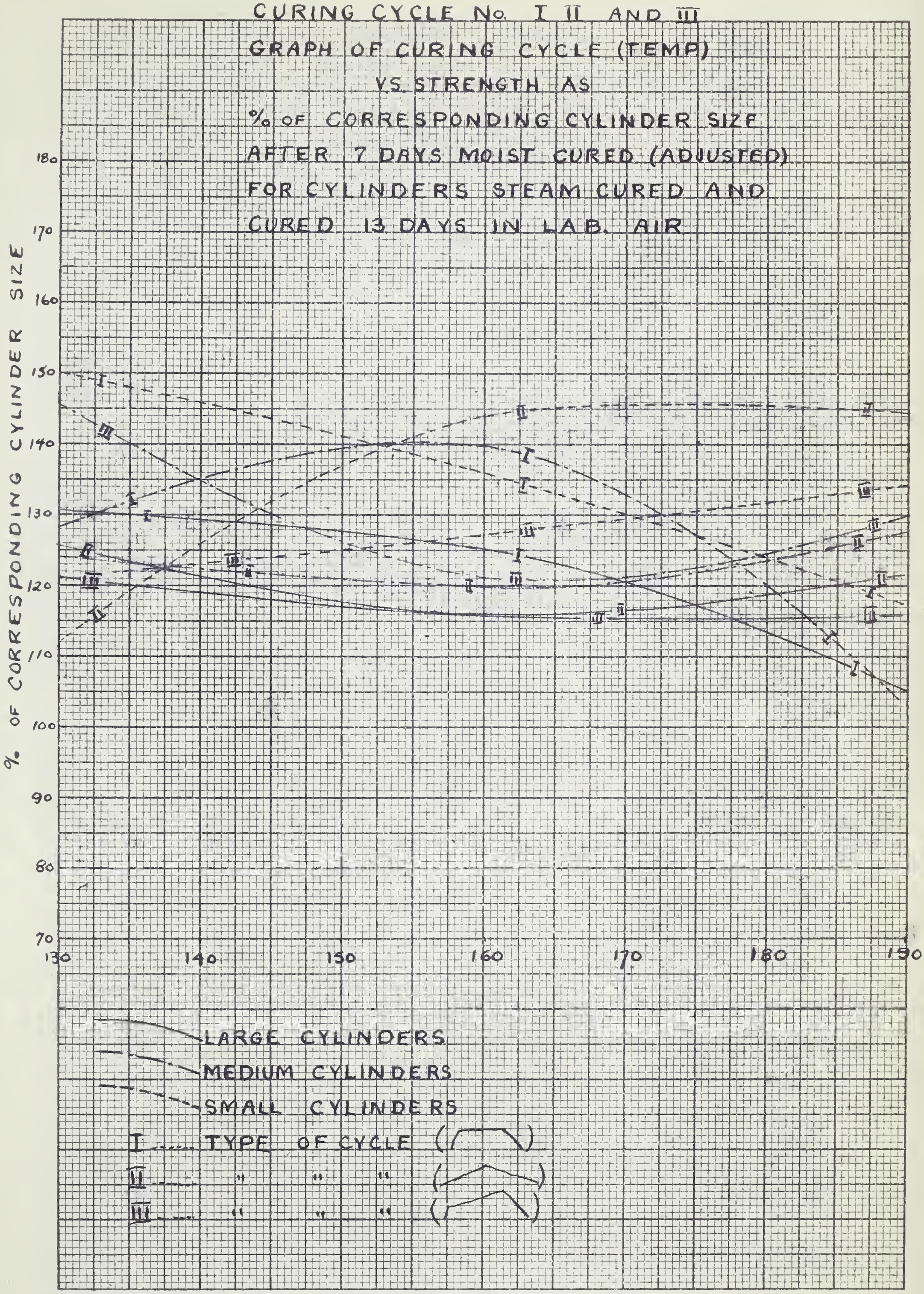
GRAPH No. 11



CURING CYCLE No. I, II AND III

GRAPH OF CURING CYCLE TEMP.
V.S. STRENGH AS
% OF CORRESPONDING CYLINDER SIZE
AFTER 7 DAYS MOIST CURING (ADJUSTED)
FOR CYLINDERS STEAM CURED, 6 DAYS MOIST
CURED AND 7 DAYS CURED IN LAB. AIR

GRAPH No 12



CURING CYCLE No. I II AND III

GRAPH OF CURING CYCLE (TEMP)

VS STRENGTH AS

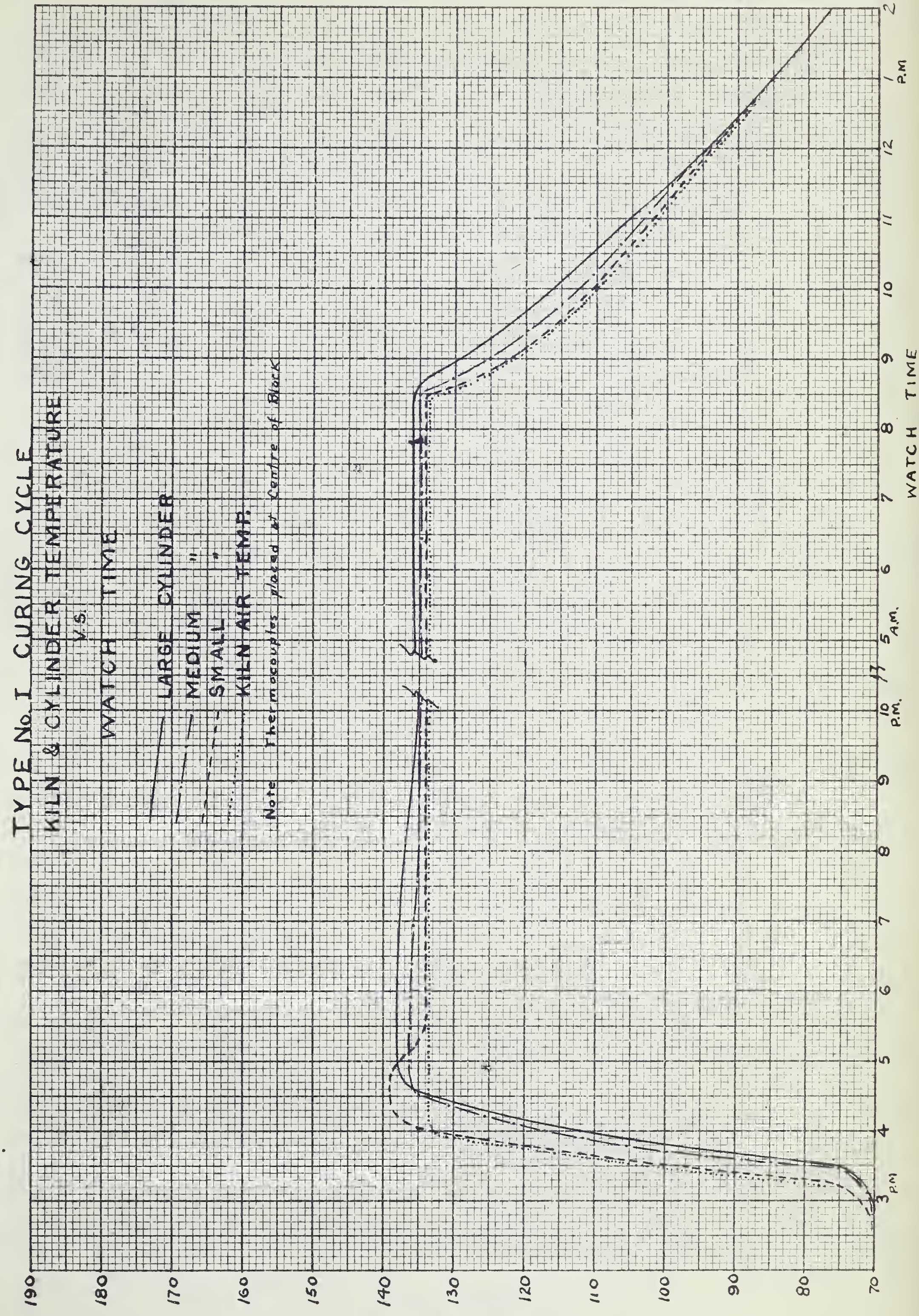
% OF CORRESPONDING CYLINDER SIZE

AFTER 7 DAYS MOIST CURED (ADJUSTED)

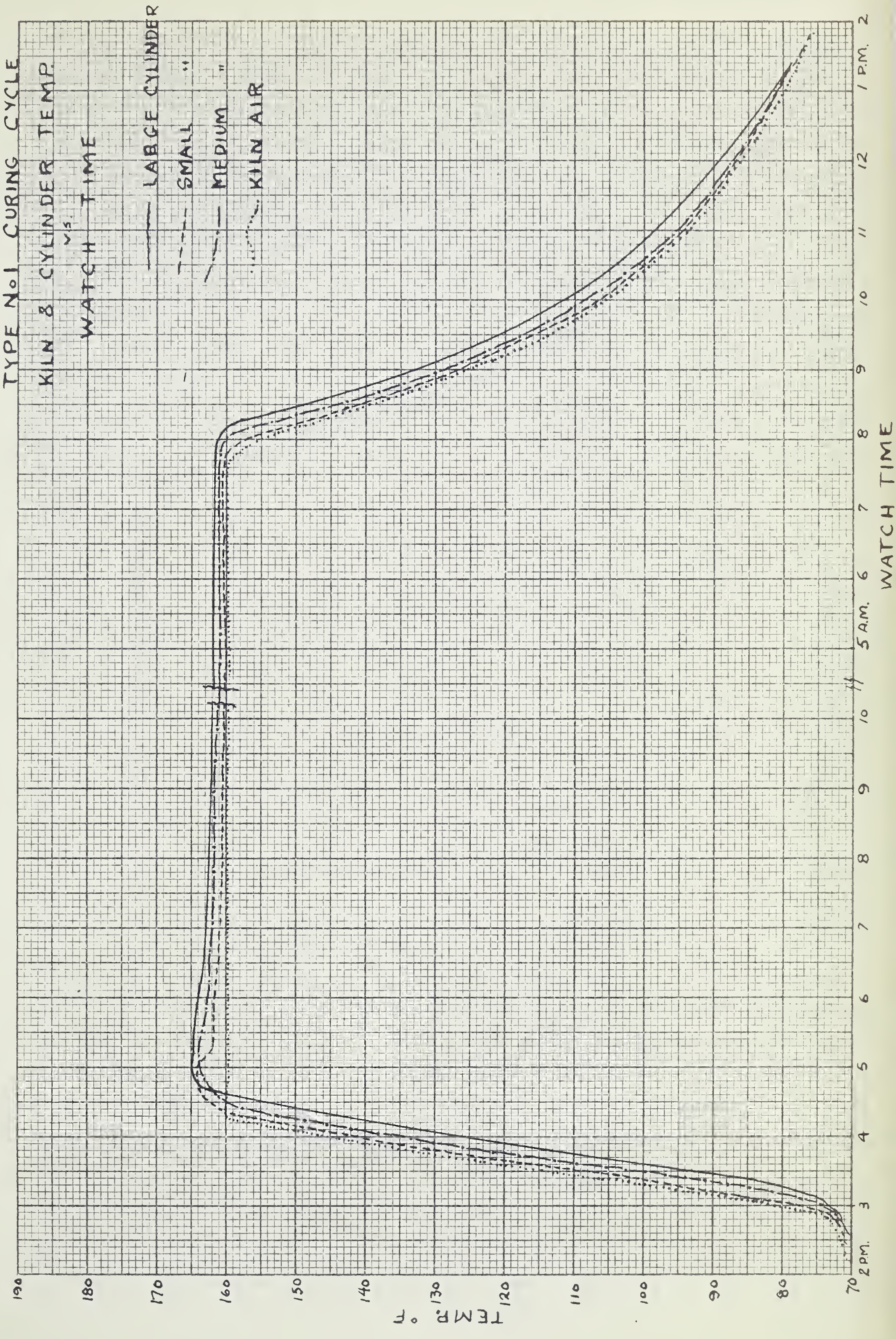
FOR CYLINDERS STEAM CURED AND

CURED 13 DAYS IN LAB. AIR

GRAPH No 13


135°F
TYPE No. I CURING CYCLE
KILN & CYLINDER TEMPERATURE
V.S.
WATCH TIME
LARGE CYLINDER
MEDIUM "
SMALL "
KILN AIR TEMP.
Note Thermocouples placed at Centre of Block
TEMPERATURE °F
190
180
170
160
150
140
130
120
110
100
90
80
70
WATCH TIME
3 P.M.
4
5
6
7
8
9
10 P.M.
11
5 A.M.
6
7
8
9
10
11
12
1 P.M.
2

GRAPH No 14

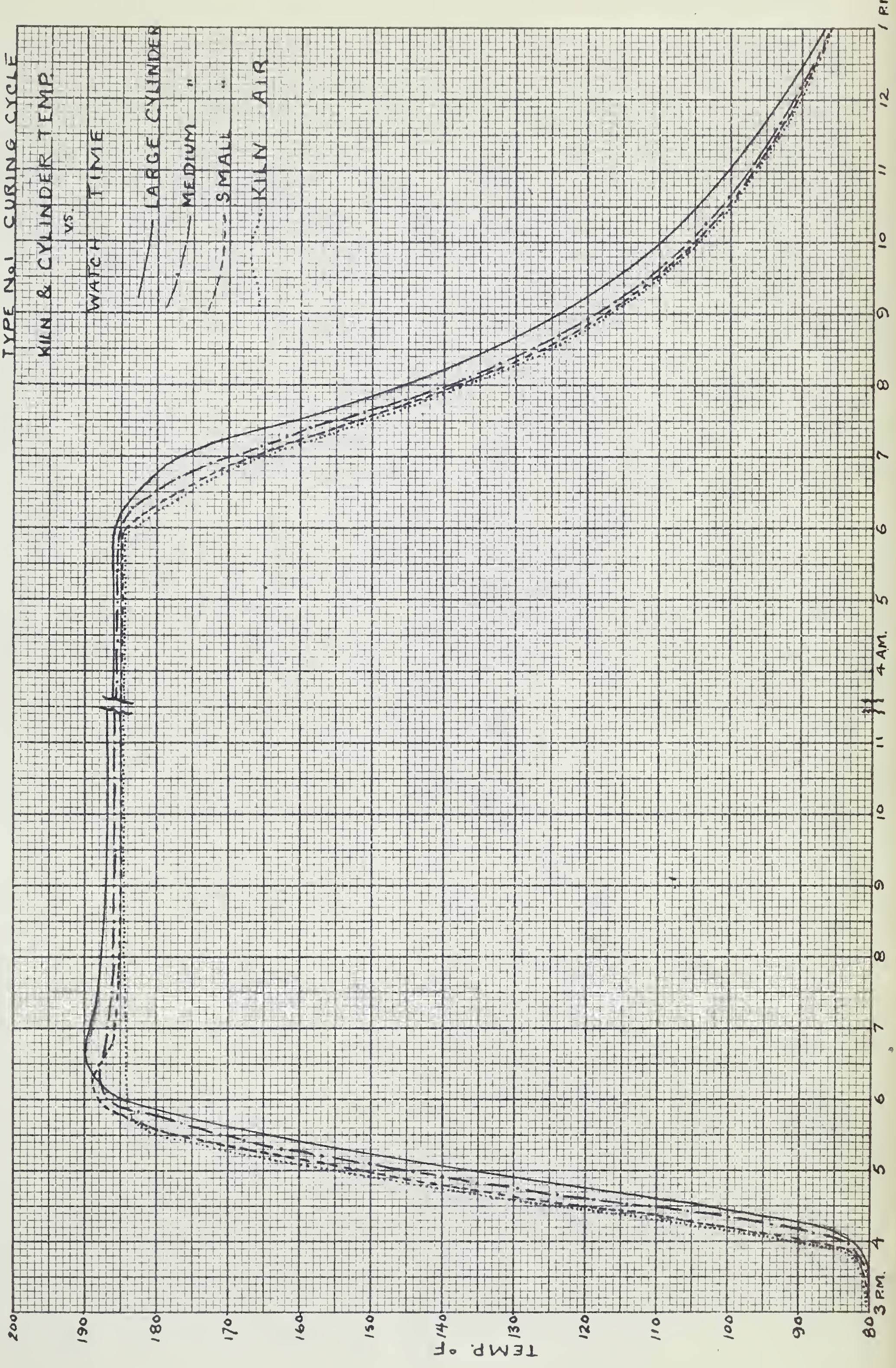


160°F

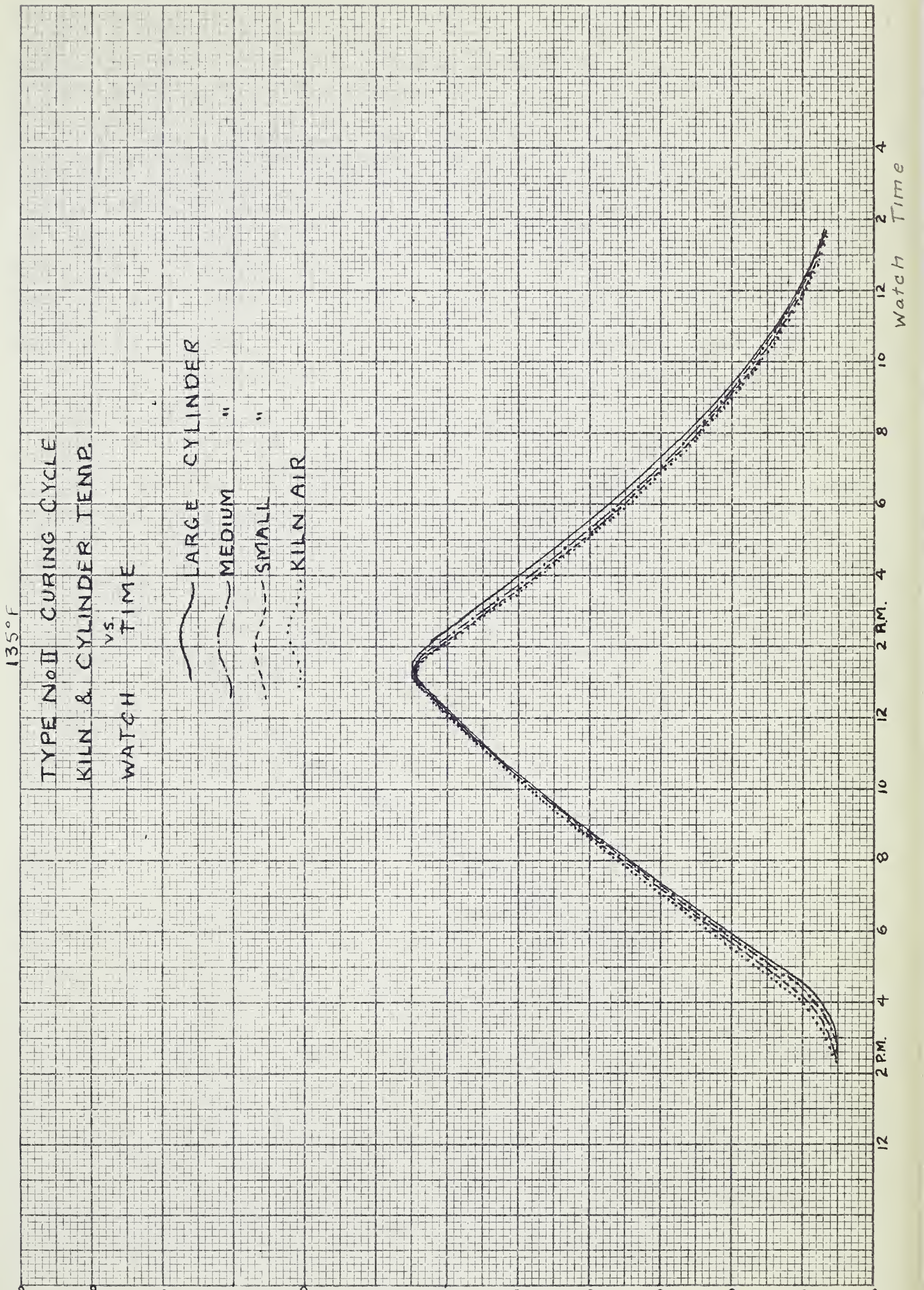
TYPE No 1 CURING CYCLE

KILN & CYLINDER TEMP. vs. WATCH TIME

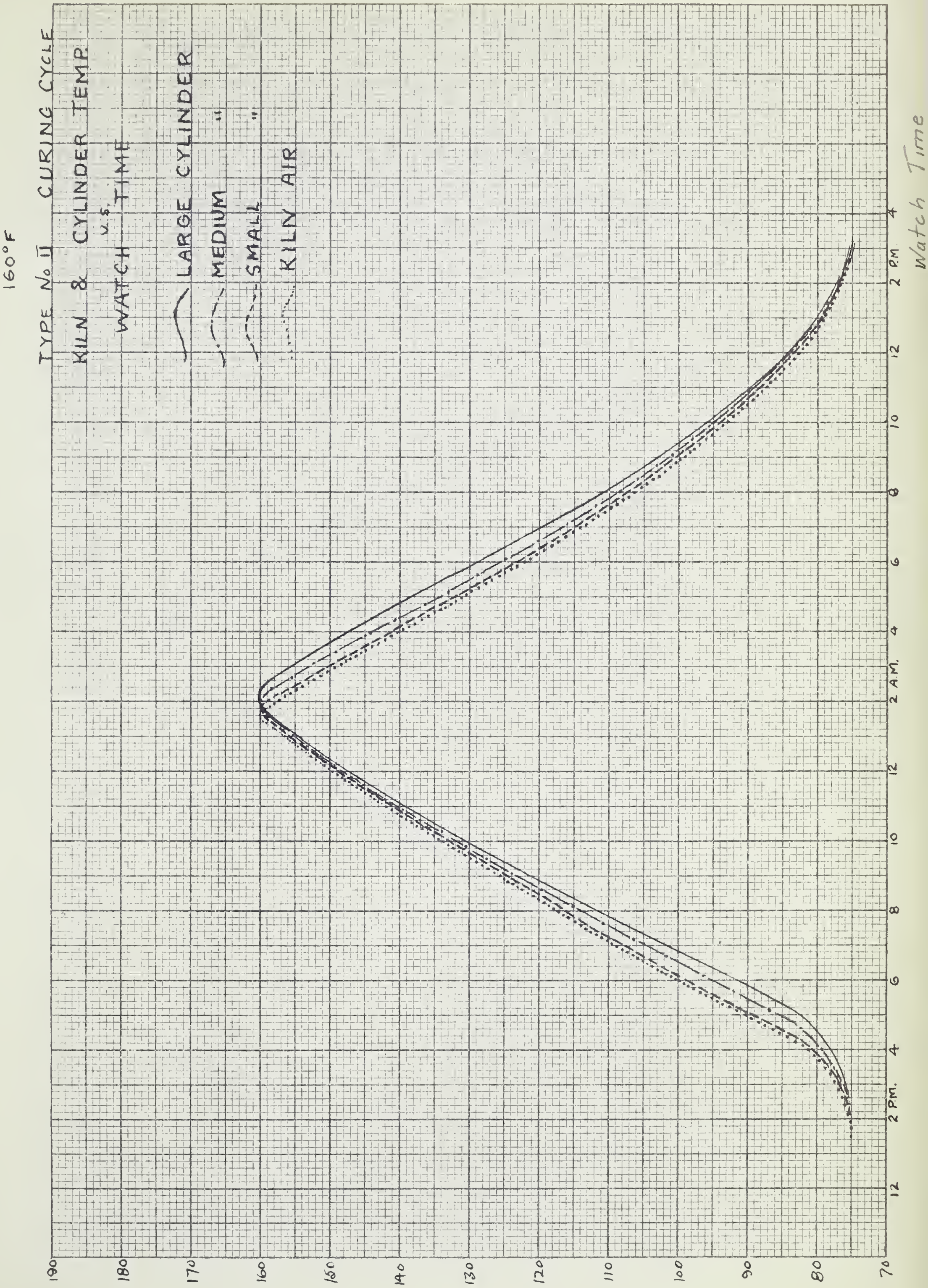
GRAPH No 15


185°F
TYPE No. 1 CURING CYCLE
KILN & CYLINDER TEMP
VS.
WATCH TIME
LARGE CYLINDER
MEDIUM "
SMALL "
KILN AIR
TEMP °F
200
190
180
170
160
150
140
130
120
110
100
90
80
3 P.M.
4
5
6
7
8
9
10
11
4 A.M.
5
6
7
8
9
10
11
12
1 P.M.

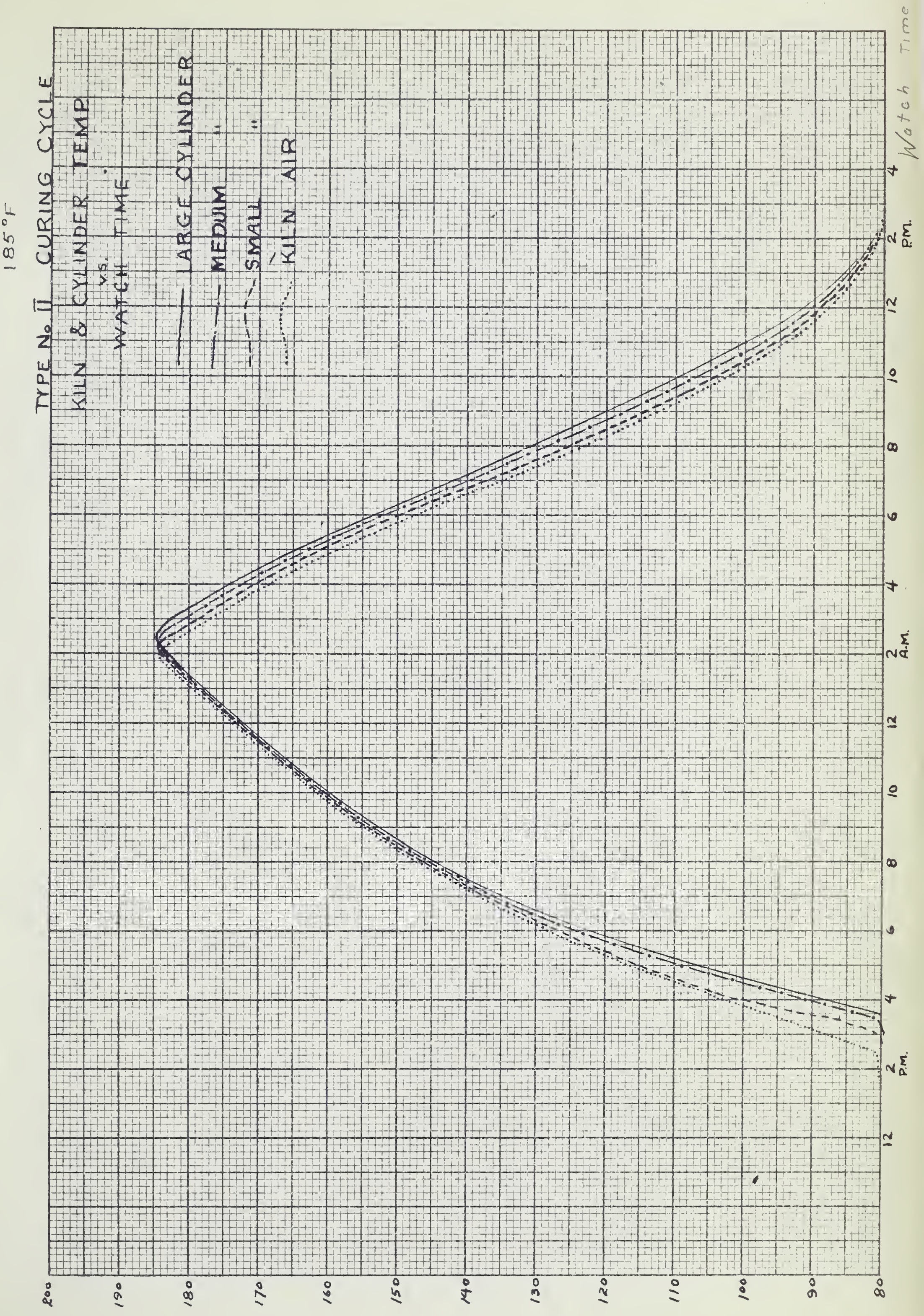
GRAPH No 16


135°F
TYPE No II CURING CYCLE
KILN & CYLINDER TEMP.
vs.
WATCH TIME
LARGE CYLINDER
MEDIUM "
SMALL "
KILN AIR
190
180
170
160
150
140
130
120
110
100
90
80
70
12
2 P.M.
4
6
8
10
12
2 A.M.
4
6
8
10
12
2
4
Watch Time

GRAPH No 17


160°F
TYPE No II CURING CYCLE
KILN & CYLINDER TEMP.
v.s.
WATCH TIME
LARGE CYLINDER
MEDIUM "
SMALL "
KILN AIR
190
180
170
160
150
140
130
120
110
100
90
80
70
12
2 P.M.
4
6
8
10
12
2 A.M.
4
6
8
10
12
2 P.M.
4
Watch Time

GRAPH No 18


185°F
TYPE No II CURING CYCLE
KILN & CYLINDER TEMP
vs.
WATCH TIME
LARGE CYLINDER
MEDIUM "
SMALL "
KILN AIR
200
190
180
170
160
150
140
130
120
110
100
90
80
12
2 P.M.
4
6
8
10
12
2 A.M.
4
6
8
10
12
2 P.M.
4
Watch Time

GRAPH No 19

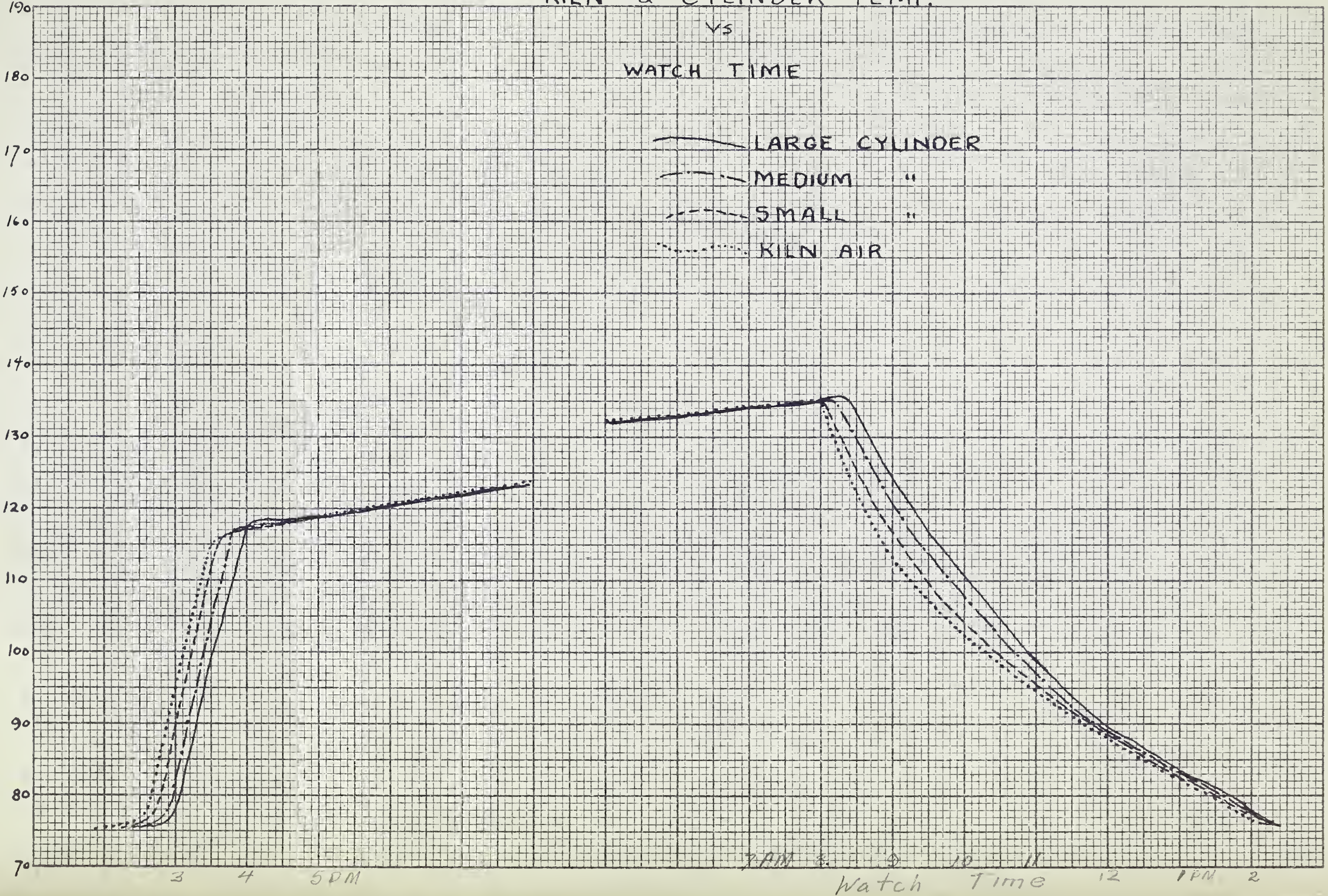
135°F

TPYE No III CURING CYCLE

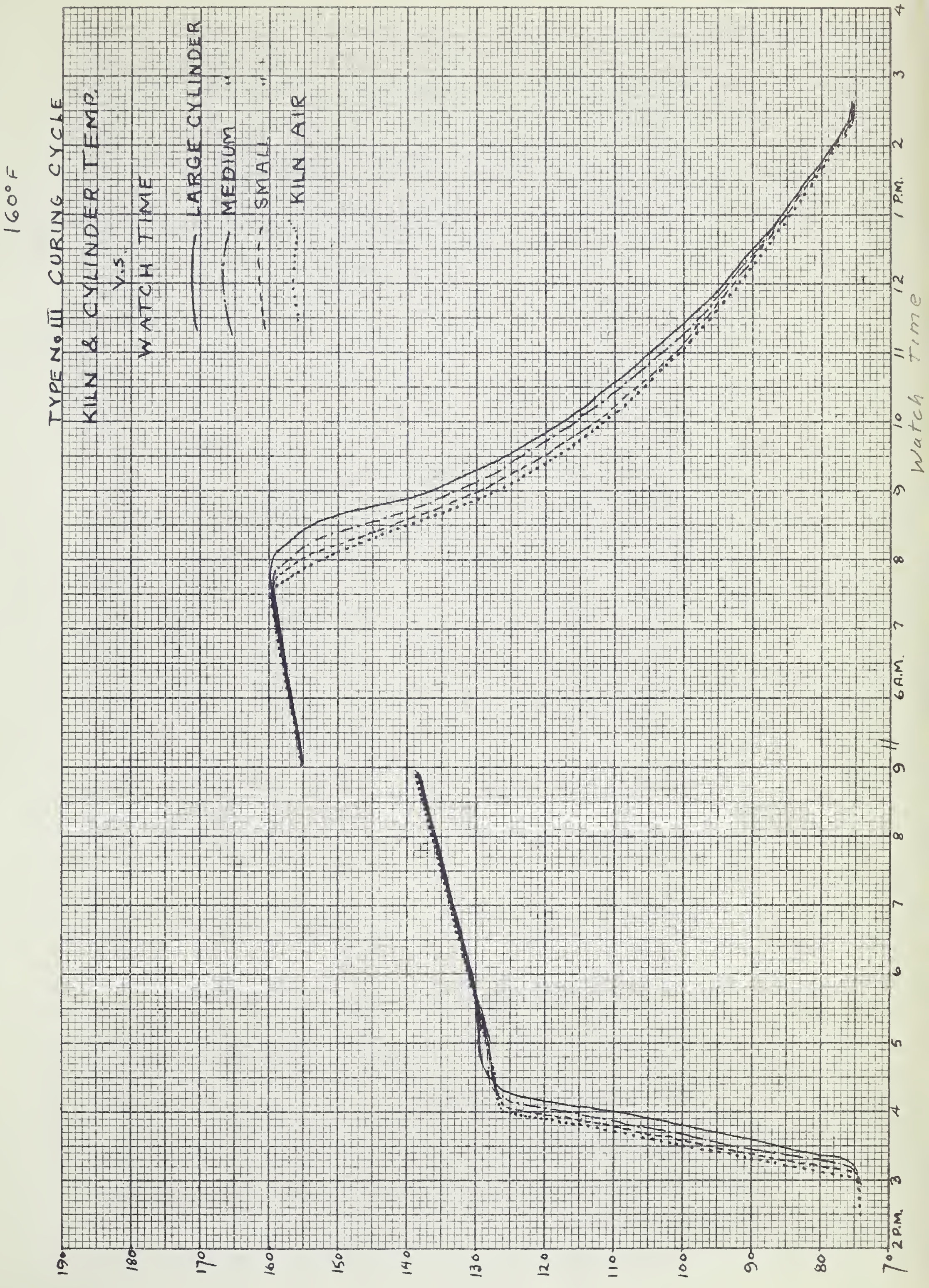
KILN & CYLINDER TEMP.

VS

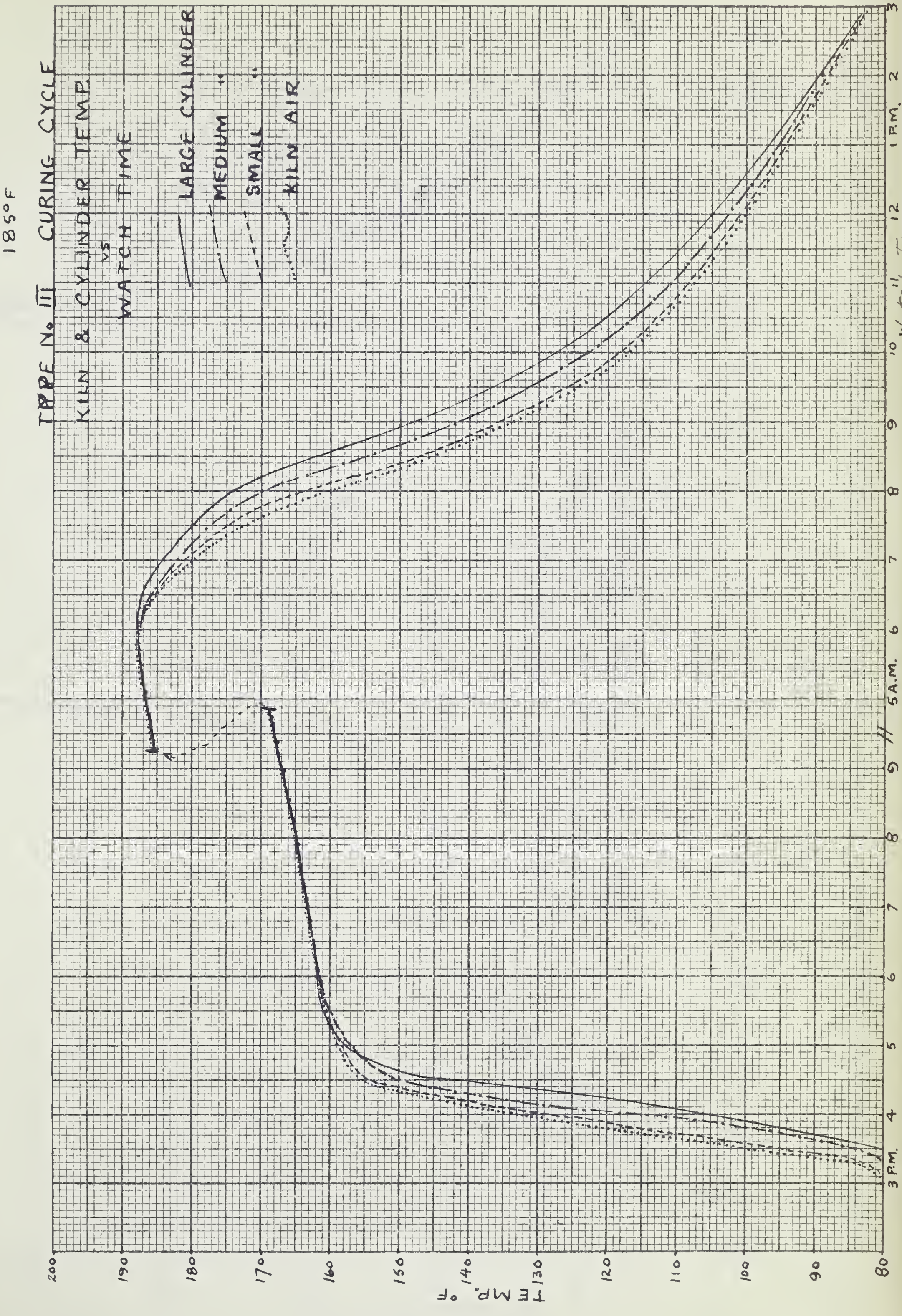
WATCH TIME



GRAPH No 28


160°F
TYPE No III CURING CYCLE
KILN & CYLINDER TEMP.
V.S.
WATCH TIME
LARGE CYLINDER
MEDIUM "
SMALL "
KILN AIR
190
180
170
160
150
140
130
120
110
100
90
80
70°
2 P.M.
3
4
5
6
7
8
9
6 A.M.
7
8
9
10
11
12
1 P.M.
2
3
4
Watch Time

GRAPH No 21


185°F
TYPE No III CURING CYCLE
KILN & CYLINDER TEMP.
vs
WATCH TIME
LARGE CYLINDER
MEDIUM "
SMALL "
KILN AIR
TEMP. °F
200
190
180
170
160
150
140
130
120
110
100
90
80
3 P.M.
4
5
6
7
8
9
5 A.M.
6
7
8
9
10
11
12
1 P.M.
2
3
Watch Time

GRAPH No 22

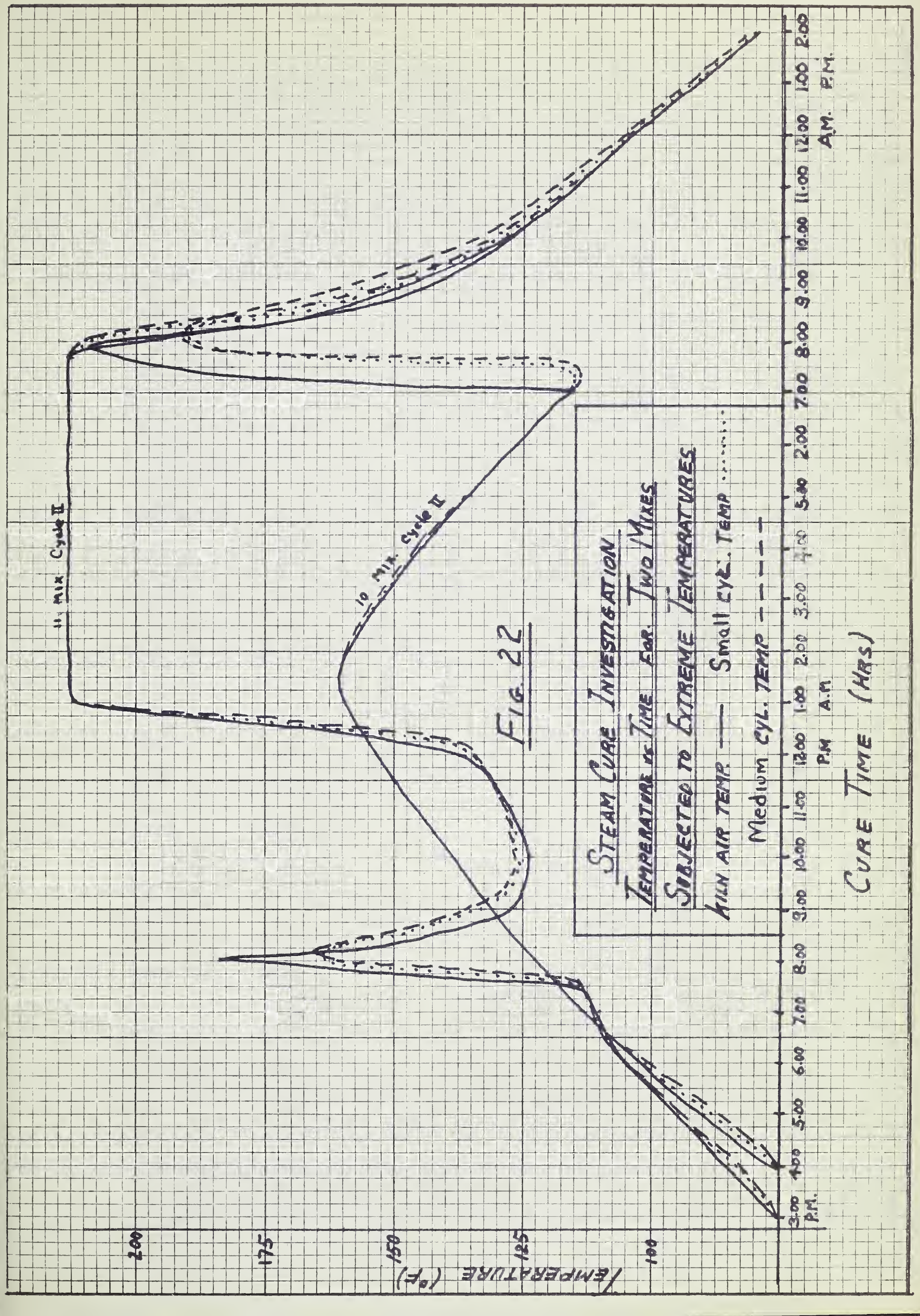


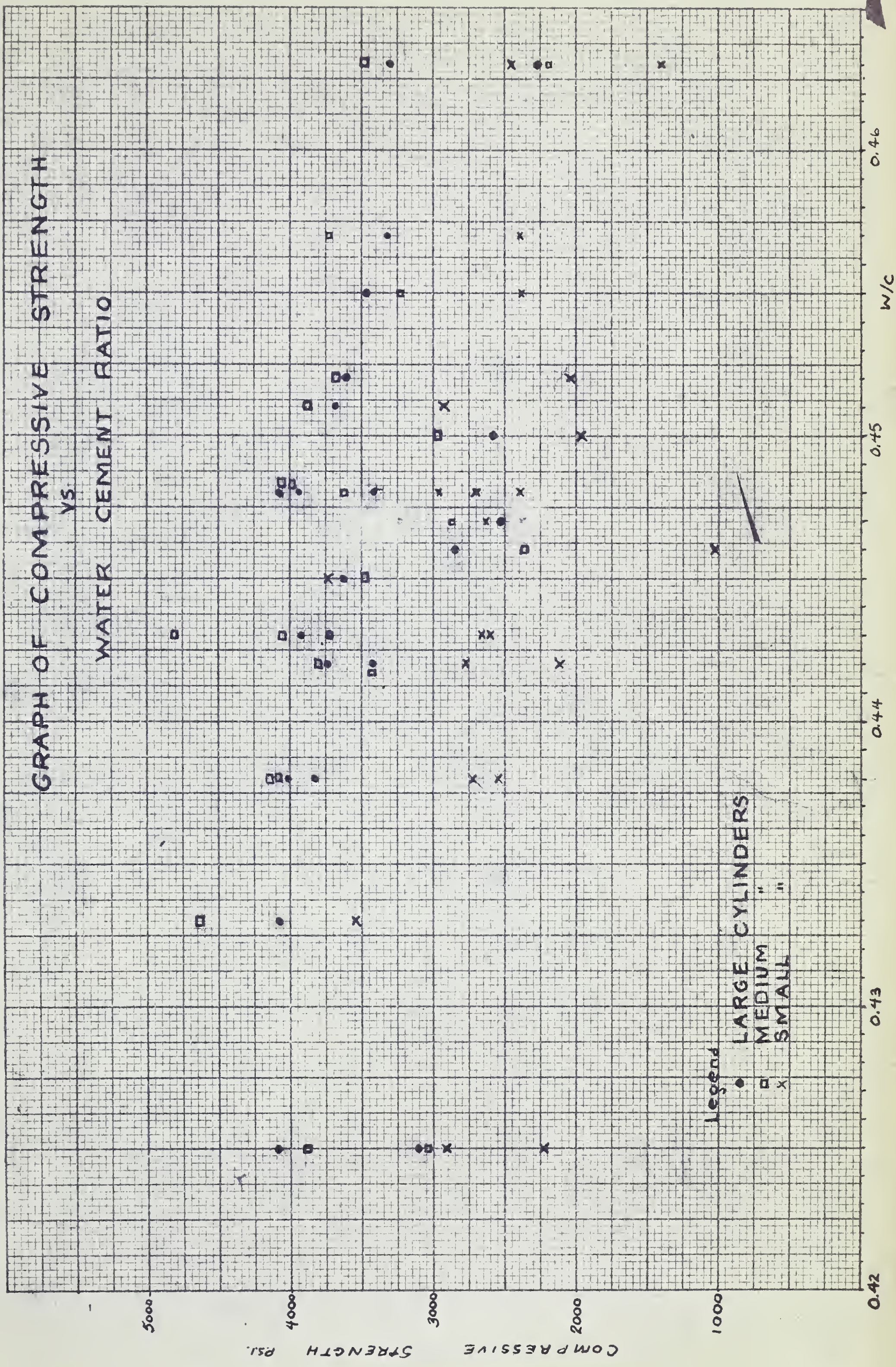
FIG. 22

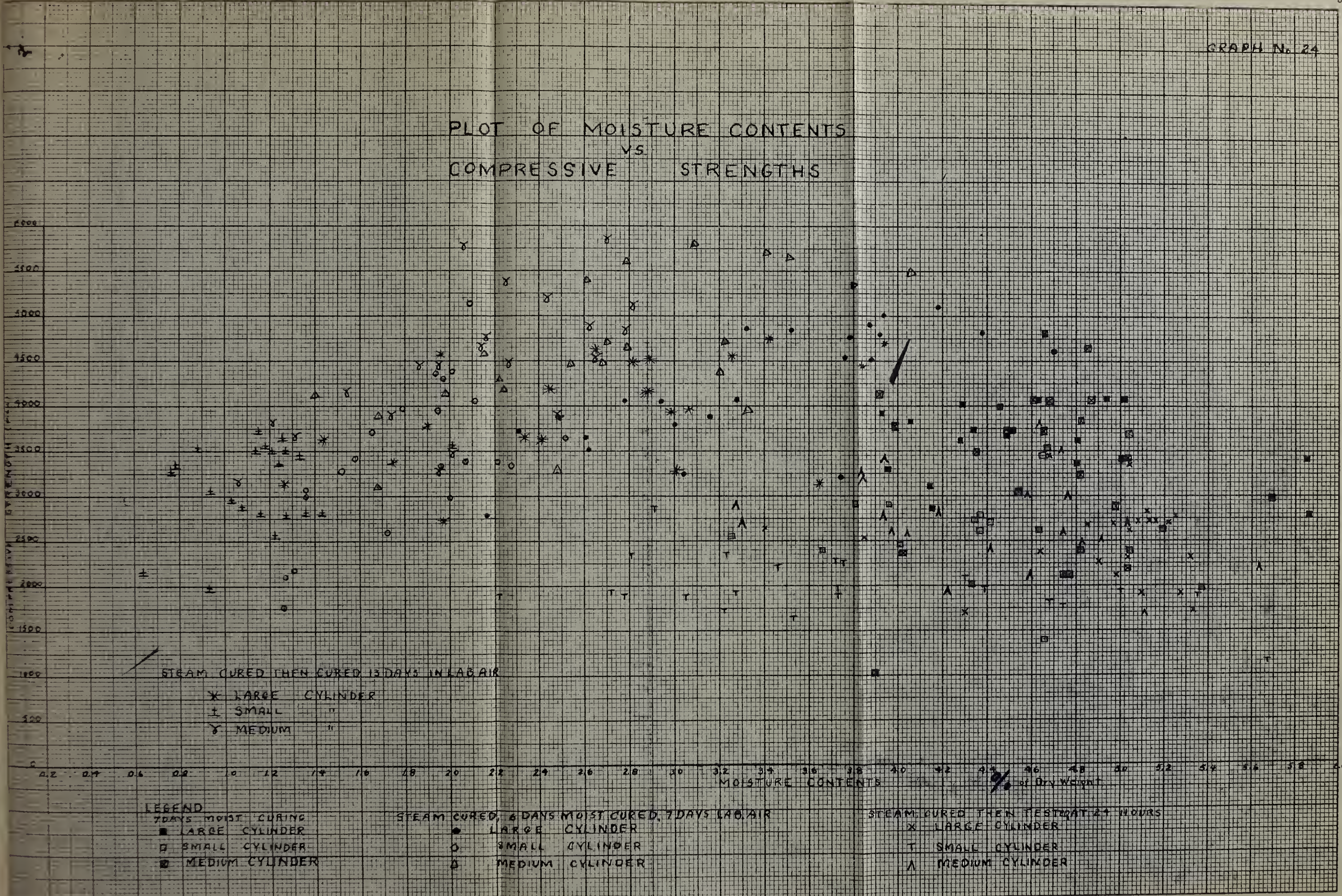
STEAM CURE INVESTIGATION

TEMPERATURE vs TIME FOR TWO MIXES

SUBJECTED TO EXTREME TEMPERATURES

GRAPH No 23


GRAPH OF COMPRESSIVE STRENGTH
VS.
WATER CEMENT RATIO
Legend
● LARGE CYLINDERS
□ MEDIUM "
x SMALL "
W/C
0.42
0.43
0.44
0.45
0.46
COMPRESSIVE STRENGTH PSI.
1000
2000
3000
4000
5000


GRAPH No. 24
PLOT OF MOISTURE CONTENTS
VS
COMPRESSIVE STRENGTHS
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.4
3.6
3.8
4.0
4.2
4.4
4.6
4.8
5.0
5.2
5.4
5.6
5.8
6.0
MOISTURE CONTENTS % of Dry Weight
STEAM CURED THEN CURED 13 DAYS IN LAB AIR
✳ LARGE CYLINDER
± SMALL "
ɣ MEDIUM "
LEGEND
7 DAYS MOIST CURING
■ LARGE CYLINDER
□ SMALL CYLINDER
⊠ MEDIUM CYLINDER
STEAM CURED, 6 DAYS MOIST CURED, 7 DAYS LAB AIR
● LARGE CYLINDER
○ SMALL CYLINDER
△ MEDIUM CYLINDER
STEAM CURED THEN TESTED AT 24 HOURS
x LARGE CYLINDER
T SMALL CYLINDER
Λ MEDIUM CYLINDER

Discussion

The experimental steam kiln as constructed for this investigation worked very well. It was possible to control the temperature and to produce almost any type of curing cycle. The kiln atmosphere had a high relative humidity value. A commercial steam curing kiln would not be quite so easy to construct as the one used in this investigation. In the investigation steam, air and water were put into the kiln in quantities that gave reasonable assurance that the required atmosphere would be obtained. With a commercial kiln this practice would not be economical. It would be necessary to obtain the services of a qualified engineer to decide on the proper amounts of steam, air and water necessary for the particular curing kiln. He would also have to specify the size of plant required to produce the necessary amount of steam and the size of the other equipment.

The curing kiln used in this investigation produced the required high relative humidity atmosphere. This was shown by the wet and dry thermocouple hydrometer and also in Table No. 1 showing the weight variations during the curing cycle. The weight of the cylinder increased when the curing cycle was started, indicating that the cylinder was taking up moisture. The weight variations did not become negative until the end of the cycle, and in some cases did not become negative even at the end of the cycle. There are not enough weight variation readings to give any quantitive

conclusions. A continous observation of the weight variations would have been more desireable. I believe a device could be constructed quite easily to take continous observations of the weight variations. A spring balance could be used and if a pen were attached to the spring balance the variations could be recorded on a drum which turned very slowly. This drum could be run from a pully attached to the cam in the remote control mechanism.

It must be realized that the weight variations include the weight of the moisture which is condensed upon the concrete specimen and upon the scale pan. This fact should not greatly change the conclusions reached from the weight variations readings. A correction factor might be determined to eliminate this effect. If moisture is being condensed during the curing cycle, it means that the kiln atmosphere must have a very high relative humidity; also, if moisture is being condensed upon the concrete specimen, there is probably enough moisture present for the proper hydration of the cement.

It would be interesting to run a series a tests without introducing extra water, or air, or both into the kiln during the curing cycle. That is, allow only steam, steam and air or steam and water to enter the kiln. An investigation of this nature would be more liable to bring out the actual importance of the theory discussed under "Thermodynamics of Steam Curing".

It is of the author's opinion that a little too much stress was put on the thermodynamics of steam curing as laid down in the beginning of this report. This opinion is based on the fact that the different curing cycles did not greatly affect the concrete strengths. It was stated in the first part of the report that Cycle No. 3 would be more or less of an ideal cycle. This was not the case in a number of instances. That is, Cycle No. 1 produced concrete strengths greater than Cycle No. 3. The idea of Curing Cycle 3 was to keep the cylinder temperature just below the kiln air temperature; thus the resulting vapor pressures within the cylinder would be less than the vapor pressure of the kiln air, with the result that moisture would move from the kiln air into the concrete block. The benefits of Cycle No. 3 might show up more readily when the kiln is operated without the introduction of extra water, or air or both into the kiln. In our investigation the relative humidity was so high that possibly the benefit gained from using Curing Cycle No. 3 was lost. However, one should not ignore the importance of thermodynamics in steam curing but probably its importance was stressed a little too much in this report.

In Table No. 3 it was found that on the average the small cylinders had a strength value of 71 per cent of the large cylinders and the medium cylinders had a strength value of 104 per cent of the large cylinders. (This is for the

moist cured cylinders). The 71 per cent value for the small cylinder certainly does not follow from the extensive investigation made by the Bureau of Reclamation (16) regarding the effect of cylinder size on the compressive strength of concrete. Using the results from this investigation, the comparative percentages should be 108.7 per cent for the small cylinder and 104 per cent for the medium sized cylinder. The low value found for the small cylinder was probably due to the method used to compact the concrete in the molds. The cylinders were compacted so as to give each unit volume of concrete the same compactive effort, with the result that the small cylinder received 10 blows from a three pound hammer, the medium cylinder received 50 blows from a 5 pound hammer and the large cylinder received 176 blows from a 5 pound hammer. The vibrational effect caused by the increased number of blows the large cylinder received probably caused the large cylinder to be compacted better than the small cylinder. This explanation does not quite follow when the medium sized cylinders are compared with the large cylinders, but the difference in the number of blows received by large cylinder and the small cylinder is greater than the difference between the large cylinder and the medium cylinder. The large cylinder received about 18 times the number of blows given to the small cylinder and only about 3½ times the number of blows given to the medium cylinder. If another investigation is to be carried out using dry mixes, it might be adviseable to use a vib-

ration machine to compact the cylinders instead of using a tamping device.

The tamping probably caused the large variations found in the strength values of the small cylinder. Because of this large variation, too much reliance should not be put on the conclusions reached from the strength values of the small cylinders. To eliminate the effect of tamping and vibration altogether, a wet mix might be used instead of a dry mix when investigating the effect of steam curing upon the different cylinder sizes.

To make the discussion of the different graphs etc. more readable, symbols will be used for references to the different curing methods, as follows:

M C - refers to the cylinders which were cured in the moist room for seven days, then tested.

S24 - refers to the cylinders which were steam cured and then tested immediately after the steaming cycle was complete.

S67 - refers to the cylinders which were steam cured, then moist cured for six days, cured in the laboratory air for seven days and then tested.

SLA - refers to the cylinders which were steam cured, then cured in the laboratory air for thirteen days and tested:

In regard to Table III, it should be noticed that the M C strengths are all higher after Mix No. 10. It was necessary to use a new batch of cement after Mix No. 10

and this fact probably caused the discrepency. Also there is quite a variation in strengths between the different mixes. To eliminate these factors all the strength values were reduced to per centages. The reduction of the strengths to per centages does not, however, eliminate all the errors. More reliable results could have been obtained had a much larger number of cylinders been broken. The investigation does not warrant a quantitative discussion, but a qualitative discussion is permissible.

Referring to Graphs No. 1 and 7 of Curing Cycle No. 1

For the medium and large sized cylinders, for maximum S24 strengths, a temperature of 160 degrees is the best, but for the S67 and SLA strengths the best temperatures are 135 degrees and 160 degrees. The temperature of 185 degrees Fahrenheit was detrimental in all cases. The largest gain in strength between the S24 and S67, SLA cylinders occured at 135 degrees Fahrenheit, next was the 160 degree temperature and the least gain in strength was at 185 degrees Fahrenheit. For the small cylinders temperatures of 160 and 185 degrees were detrimental as far as the S67 and SLA strengths are concerned. However, for the S24 strengths there is not a great deal of difference between the different temperatures, but a temperature of 135 degrees Fahrenheit is somewhat better than the other two temperatures for the small cylinders..

Referring to Graph No. 2 and 8 of Curing Cycle No. 2

The temperature of 185 degrees Fahrenheit seems

to be the best temperature. This is contrary to the results of cycle number one, but with cycle number two the temperature rose very slowly to up to 185 degrees Fahrenheit and the kiln was at that temperature for only a short time. The S24 strengths are higher for the 185 degrees Fahrenheit and lower for the other two temperatures, 135 degrees Fahrenheit being the lowest. The gain in strength from the S24 to the S67 and SLA seems to follow from Cycle No. I. The gain in strength from the S24 to the S67, SLA is the greatest for the temperature of 135 degrees Fahrenheit but for the temperatures for 160 degrees Fahrenheit and 185 degrees Fahrenheit the gain in strength is about equal. Since the S24 strengths at 185 degrees Fahrenheit were greater, this would make the S67 and the SLA strengths greater at a temperature of 185 degrees Fahrenheit than at a temperature of 160 degrees Fahrenheit. It is probable that the rate of gain of strength was not greatly affected, but that the final amount of gain was affected between the two temperatures of 165 degrees and 185 degrees Fahrenheit. If long-time tests were made, it is probable that the temperature of 135 degrees Fahrenheit would give the greatest strength, 160 degrees Fahrenheit the next and 185 degrees Fahrenheit the least final strength value. This fact agrees with finding of other investigators, who have reported, that the final concrete strength is reduced through the use of steam curing.

Referring to Graphs No. 3 and 9 of Curing Cycle No. III

In Cycle No. 3 the S24 strengths do not vary greatly with the temperature. However, the gain in strength between the S24 and the S67, SLA decreases with increasing temperatures. Cycle No. 3 differs from Cycle No. 1 in that the S24 strengths of Cycle No. 3 are not reduced at 185 degrees Fahrenheit as they were in Cycle No. 1. This is probably due to the slow rise to temperature as compared with the quick rise to temperature of Cycle No. 1.

From the discussion so far one might say: (1) The rate and amount of strength gain after steam curing is decreased with increased curing temperatures; (2) The detrimental effects of high temperatures are somewhat abated when the rate of temperature rise is considerably reduced and the high temperatures are maintained for only short periods of time.

Referring to Graph Nos. 4 to 6 and 10 to 12 Comparing the Different Curing Cycles

It is rather difficult to pick out the best curing cycle as there are a number of factors that must be taken into consideration. The main object in steam curing is to obtain high early strengths but in doing so one must not disregard the long-time strength of the concrete. Therefore, when trying to pick the best cycle from the cycles used in this report, one must put considerable stress on the strength values for the S24 cylinders without disregarding the strength values for the S67. It must be

remembered also that cycles affect the three sizes of cylinders in a somewhat different manner. It would be desireable to pick a curing cycle which gives good results for all three cylinder sizes.

Cycles No. 1 and 3 at 185 degrees Fahrenheit are eliminated because of the detrimental effect of the high temperature upon the concrete. Another cause for their elimination is the economics of running a kiln at such a high temperature.

Cycle No. 2 at 135 degrees Fahrenheit and 160 degrees Fahrenheit is eliminated because of the low S24 strength values at these temperatures. The small cylinder showed favorable strength values at 160 degrees Fahrenheit using Cycle 2, but the other two cylinder sizes did not.

To eliminate Cycle No. 2 at 185 degrees Fahrenheit is a little more difficult. For the large cylinder the S24 strengths were below the S24 strengths for the other two cycles run at the two lower temperatures, but for the other two cylinder sizes the S24 strength was greatest for Cycle No. 2. For the medium sized cylinder, Cycle No. 1 at 160 degrees Fahrenheit has S24 strengths comparable to Cycle No. 2 at 185 degrees Fahrenheit. When the S67 and SLA strengths are considered, Cycles 1 and 3 are better than Cycle 2 at 185 degrees Fahrenheit.

To make a choice between the remaining cycles is hardly warranted in this investigation. The 135 degrees Fahrenheit temperature seems to give the best results for

the small cylinders while the 165 degrees Fahrenheit temperature gives the best results for the large cylinder with the medium cylinders coming inbetween these two temperatures.

From the discussion on cycles the following conclusions are justified:

(1) The type of curing cycle does affect the concrete strengths to a certain extent, but the temperature at which the curing cycle is run is a more important factor. One type of cycle may give good results when operated at one temperature and another type of curing cycle may give good results when operated at another temperature.

(2) For better results, lower temperatures should be employed for smaller sized specimens.

Referring to Graphs No. 7 to 12

Another item to be noticed in these graphs is the relative positions of the lines indicating the strength values of the large, medium and small cylinders. In the majority of cases the highest strength value is found in the small cylinder, the next strength value in the medium cylinder, and the lowest in the large cylinder. This would indicate that the beneficial results of steam curing increase as the size of the concrete specimen decreases. This fact is also indicated in the average values as computed in Table 3.

On comparing the S67 and SLA strengths in the graphs, one finds that there is not much advantage in moist curing after steam curing. This factor is again emphasized

when the averages in Table 3 are compared. A 5 to 10 per cent gain in strength is all that is obtained in the majority of cases. In a number of cases the SLA strengths were above the S67 strengths. This could be due to experimental errors and the fact that the SLA cylinders were in a drier condition when tested.

Referring to Graph No. 24 of the Moisture Contents

For the MC and S24 points plotted on the graph there is a trend indicating that the lower moisture contents gave the higher compressive strengths. This follows what a number of investigators have found out. However, for the S67 and SLA, the trend is in the other direction. It would be very difficult to reach any conclusions from the moisture content evaluations because of the large number of other factors entering into the picture. The different steam curing cycles, different temperatures, different water cement ratios, variations in concrete strengths and errors in laboratory technic all enter into the graph, making it very difficult to draw any conclusions. In nearly all cases the smaller the cylinder was, the drier the concrete.

The results from Mix No. 10 and Mix No. 11 bring out another interesting point.

From the results of Mix No. 10 it would seem that adverse curing conditions at the end of the curing cycle do not affect the compressive strength of the concrete. From the results of Mix No. 11 it would seem that adverse curing conditions occurring throughout the curing cycle

do considerably reduce the concrete strength. These conclusions, although they seem very plausible, should not be made definit until more results of this nature are obtained.

Conclusions

One of the main objects of this investigation was to build a suitable laboratory steam curing kiln. The steam kiln as built worked very well and fulfilled the requirements as stated on page 20. The conclusions reached from the remainder of the investigation must be necessarily restricted because of the relatively small number of cylinders made and tested. The conclusions reached from this investigation, concerning steam curing of concrete at atmospheric pressures, and employing a system having a high relative humidity value are:

(1). Reasonably high early concrete strengths are obtained.

(2). The rate and amount of strength gain after steam curing are decreased with increased steam curing temperatures.

(3). The detrimental effects of high temperatures are abated when the rate of temperature rise is very slow and the high temperatures are not maintained for long periods of time.

(4). The type of curing cycle employed does affect

the concrete strengths to a certain extent, but the temperature at which the curing cycle is run is a more important factor.

(5). For better results, lower steam curing temperatures should be employed for smaller sized concrete specimens.

(6). Steam curing is more beneficial the smaller the size of the concrete specimen for equal amounts of steam curing.

Suggestions for Other Investigations on the Effect of Steam Curing Upon Concrete

1. A more intensive investigation similar to the one carried out in this report. The curing cycles should be run at four or five different temperatures and the effect of not introducting air, extra water or both into the kiln could be investigated.
2. Effect of steam curing upon the durability of concrete.
3. Effect of steam curing upon the modulus of rupture and modulus of elasticity of concrete.
4. Effect of steam curing upon different concrete mixes.
5. Effect of steam curing upon the long time strengths of concrete.
6. Effect of steam curing upon airentrained concrete.
7. Effect of different admixtures upon steam cured concrete.

PART II

A Short Investigation into the Effect of Steam Curing upon Bond Strengths

Introduction

The demand for precast reinforced concrete units is increasing. Precasting is becoming a major factor in the choice of reinforced concrete as a construction material because of the ever-rising cost of labor and materials. The advantages of precasting are not, however, confined to savings in cost and materials. Since it is a planned method of construction, comparable to factory production, its use also assures a better control of quality and speedier completion of the project. The units are made by mass production methods and, as in the concrete block industry, the curing cycle is under critical examination. To speed the curing cycle steam curing is feasible. While the effect of steam curing upon the concrete is being investigated, very little work has been done concerning the effect of steam curing upon the bond strength. In connection with high pressure steam curing it was found that the bond strength was lowered. No material was found on the effect of steam curing at atmospheric pressure upon the bond strength. Therefore it was decided to carry out a short investigation into the effect of steam curing at atmospheric pressures upon the bond between concrete and steel. Time was not available for an intensive program so this investigation is in the nature of an introduction to give some information on testing procedure, difficulties encountered and other pertinant information.

Factors to Be Considered

Present Knowledge

Considerable knowledge has been gained regarding the bond between concrete and steel; an excellent summary is given in Mansfield (2).

Some of the main features to be considered in the various papers in the bibliography are:

1. For current concrete mixes, bond resistence does not increase in proportion to the strength of the concrete.
2. Bond strength is greater for a dry concrete test specimen than for a saturated concrete specimen.
3. A longer period of moist curing will increase the bond strength.
4. Vibration up to nine hours after pouring is beneficial to the total bond which is developed by the bars. The reason is probably that vibration reduces the water gain which tends to form around the bars.
5. Up to $\frac{L}{D} = 24$, the total bond resistance increase with added length of embedment, but beyond 24 diameters extra embedment develops little added resistance.

Considerable knowledge has been gained concerning the physical variations in both the steel and concrete on the total bond stress developed, but very little is known regarding the effect of steam curing upon bond strength.

Nature of Bond

All of the investigations show that bond strength can be separated into two distinct elements, adhesive resistance and sliding resistance. The true action of the adhesive resistance is not fully understood but it must be overcome before the sliding resistance comes into effect. The sliding resistance comes into effect after the bar has started moving and it is probably due to the irregularities in the surface of the bar moving past the corresponding deformations in the concrete. The sliding resistance or maximum bond strength is nearly always higher than the adhesive resistance. In practice the adhesive resistance is the most important because once the adhesive resistance is overcome the deflections in the structure become excessive.

Measuring Bond Strength

In investigations of this nature the pull-out test is nearly always used. The pull-out test will give the best relative results. That is, variations in bond strength due to the different methods of curing will show up quite readily. The bond strength obtained in this manner will not be the actual values of bond strength gained in practice but will be very close to the proper values. In the computations of bond strength, the bond is assumed to be uniformly distributed throughout the full length of embedment. Also, in pull-out tests an arbitrary value of total slip of the bar (usually about 0.0001 inches) is taken to indicate the over-

coming of adhesive resistance. Thus we can see that the bond strength found in this manner is only approximately correct but the relative values found are accurate.

Thermodynamic Considerations

The thermodynamic considerations will be similar to Part 1. However, a difference might occur because of having the steel exposed while curing. The thermal conductivity of concrete is approximately 14 BTU per hour per square foot per fahrenheit degree temperature difference per inch thickness and the thermal conductivity of the reinforcing bar is about 430 BTU per hour per square foot per fahrenheit degree difference per inch thickness. From this information one can see that the steel will conduct more heat than the concrete. Now if the steel is exposed as it is in an ordinary pull-out test specimen, the concrete surrounding the steel will have a higher temperature than for example the concrete half way between the steel and the outside of the test specimen. This difference in temperature will cause the concrete surrounding the steel to lose moisture (as discussed in Part 1). When the moisture movement is taken into consideration, will there be enough moisture left for hydration? This effect is counter-balanced by the area of steel and area of concrete exposed. The area of concrete exposed will be much larger than the area of steel. This will affect the curing mostly during the heating cycle. When a constant temperature in the kiln is reached the

resulting temperature differences will not be great, and as long as the relative humidity of the kiln air is high, sufficient moisture will be present for hydration. (This has been more fully discussed in Part 1). From the above discussion one might conclude that the exposure of the steel to the kiln atmosphere will have little effect upon the resulting concrete and bond strengths as compared to having the steel covered or enclosed within the concrete unit.

Other Items

To predict from theoretical considerations the effect of steam curing upon bond strengths would be difficult since the true nature of the bonding action of concrete to steel is not known. The water gain *may be* affected by steam curing since steam curing seems to have considerable effect upon the moisture movement and moisture content of the block. Water gain is a phenomenon that is evidenced by the moisture sheen that gathers, soon after casting, at the surface of even stiff mixes. Water gain is apparent visually on the mortar bed below any horizontal bar. Where water gain occurs, the bond strength is reduced. This effect can be overcome somewhat by using pull-out specimens which are cast vertically.

The effect of steam curing upon the shrinkage of the concrete *might* affect the resulting bond strength. Wig (1) states that the bond strength of intial slip is not appreciably affected by shrinkage during curing, but that

the effect of this shrinkage is to increase the maximum bond strength. These tests in Wig (1) were carried out for ordinary curing procedures.

Laboratory Equipment

1. Curing Kiln

The curing kiln used in this investigation was the same one that was used in the investigation of the Effect of Steam Curing upon Concrete and it has been fully described in Part 1 of this report. To place the pull-out test specimen in the kiln, it was necessary to remove the racks from the kiln.

2. Mixer

The mixer used in this investigation was a $1\frac{1}{2}$ cubic foot Lancaster, type - S.K.G. Serial No. 303, manufactured by Volta Manufacturing Company Limited of Welland, Ontario. See Figure (126), page (103).

3. Load Testing Machine

The testing machine used was a Baldwin Southwork Tate-Emery Testing Machine. The testing machine had three loading ranges - 0 to 10000 pounds, 0 to 50000 pounds and 0 to 20,000 pounds. The machine was accurate to about 0.25 per cent.

See Figures (11a) and (11b), page (102).

4. Moist Room

The moist room was a small 10 by 10 by 3 room lined with cement plaster. Shelves and racks were provided within the moist room to hold the test specimens. The atmosphere within the moist room was kept at a high relative humidity and at a constant temperature of 70 degrees Fahrenheit.

5. Molds

Steel cylindrical molds were used. The molds had a diameter of 6 inches, a height of 12 inches, and a thickness of 1/8 inch. See Figure (12a), page (103).

6. Device to Hold Steel Perpendicular While Molding

See Figure (12a), Page (103).

7. Covers for Steel

When the pull-out test specimens were steam cured, covers over the steel consisted of two cylinders, one inside the other. The space between the cylinders was filled with zonolite. See Figure (14), page (105).

8. Drying Cabinet

The drying cabinet consisted of a 2' by 3' by 4' insulated cabinet with two large doors. The cabinet was thermostatically controlled and operated at a temperature of about 90 degrees Centigrade.

9. Shovels

Trowels

Slump Cone

Tamping Rod, etc.

(See Figure (12a), page (103).

10. Thermocouples

These were attached to the Brown Recorder.

11. Ames Dial

This was used with a device to hold it in place while the load was applied to the test specimen. See Figure (14), page (105).

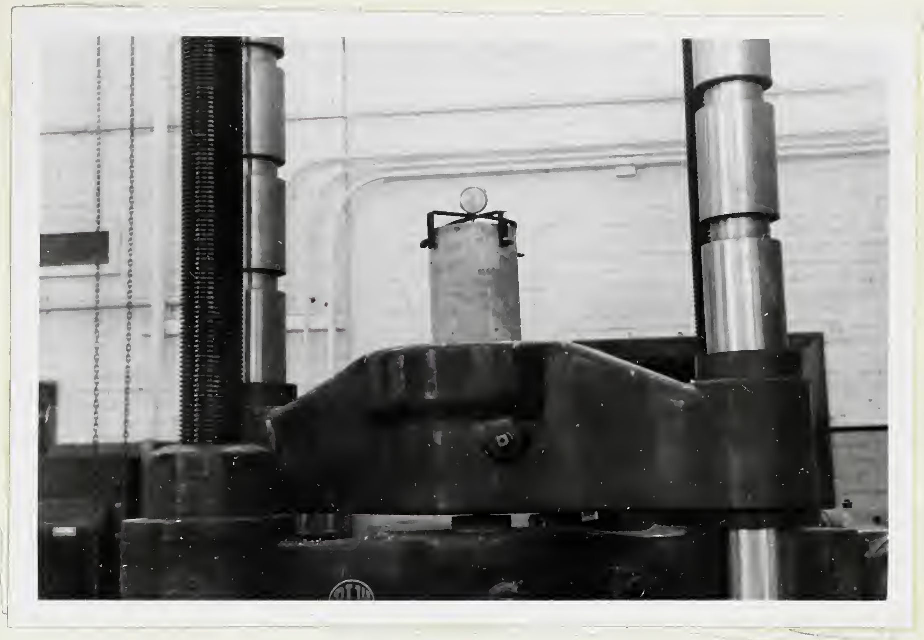


Fig. 11 (a) Pull out Test

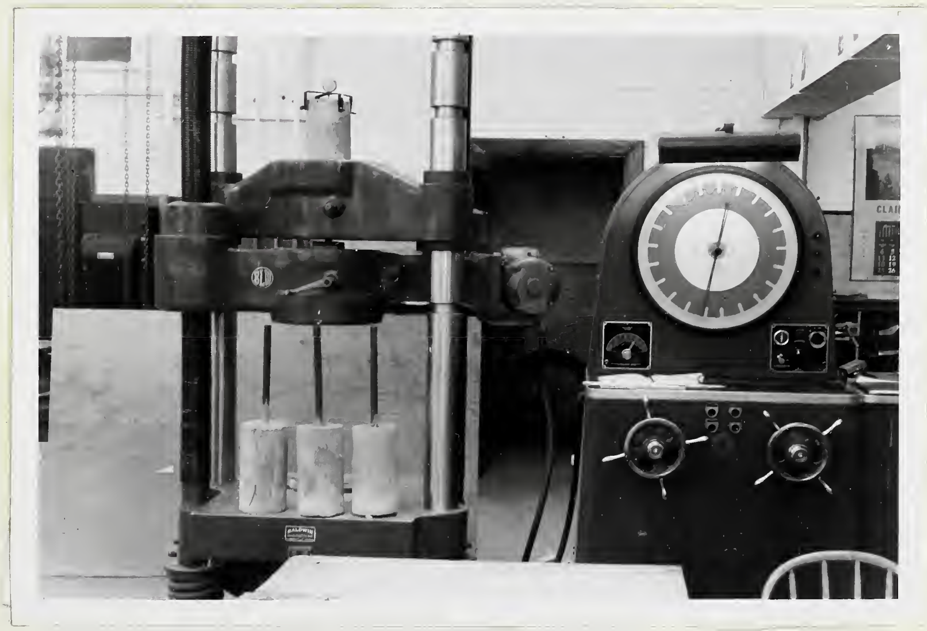


Fig. 11 (b) Testing Machine

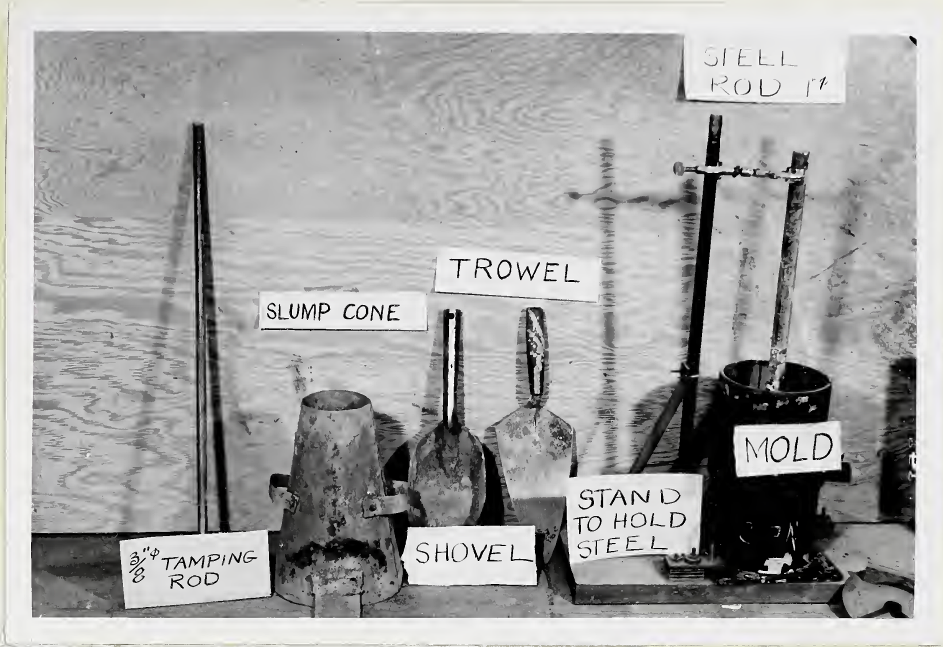


Fig. 12 (a) Above

Miscellaneous

Equipment

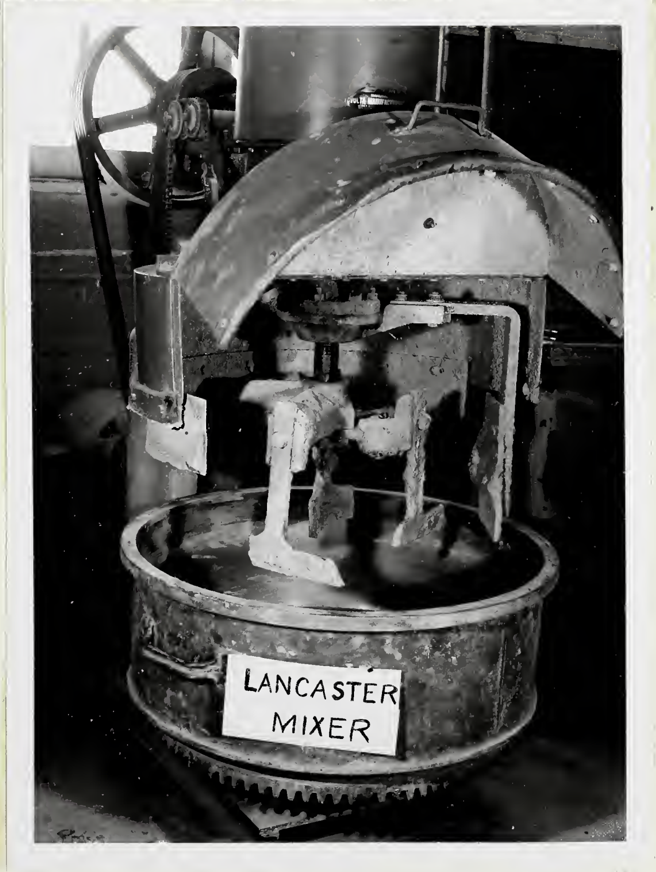
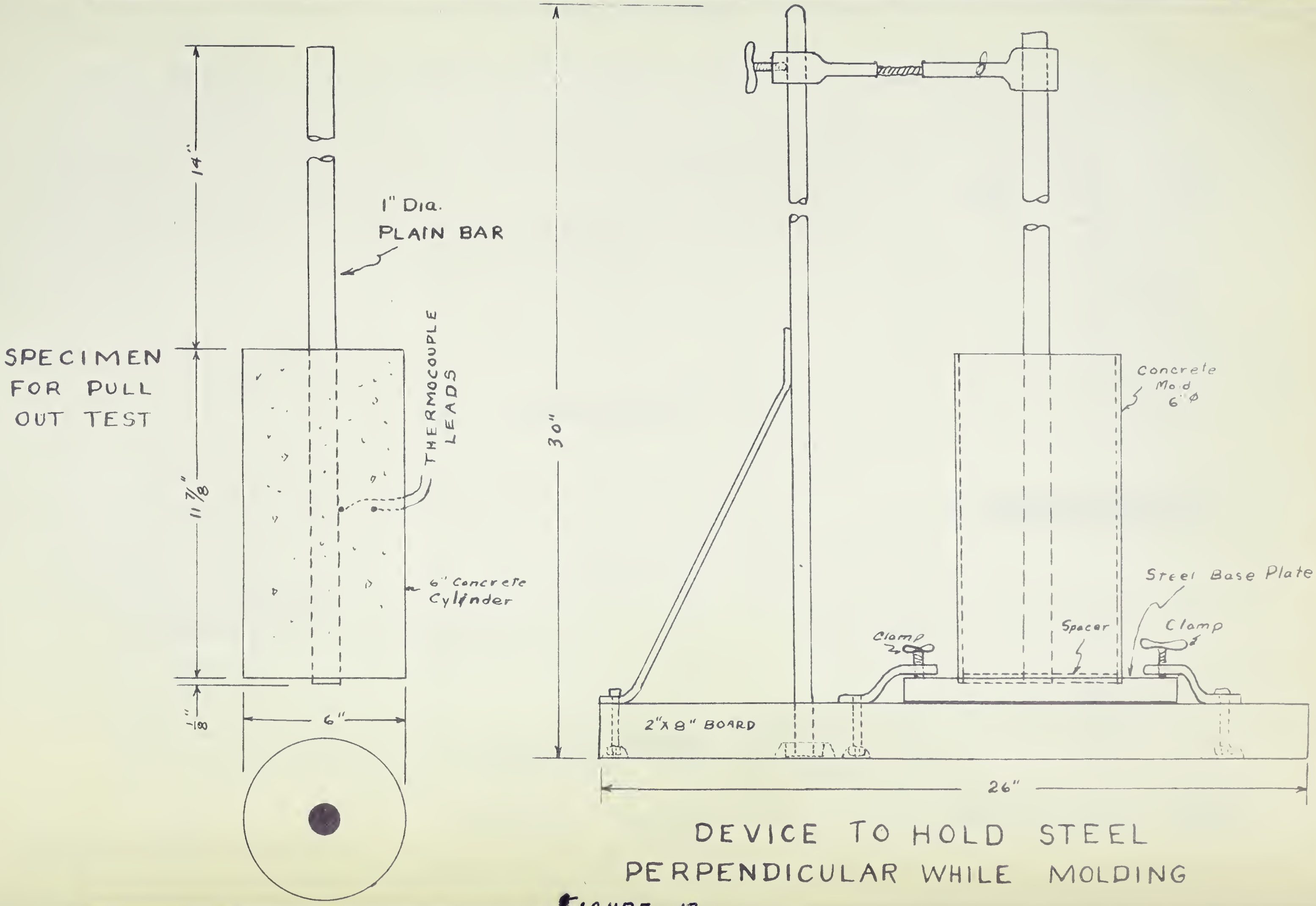


Fig. 12 (b) Right

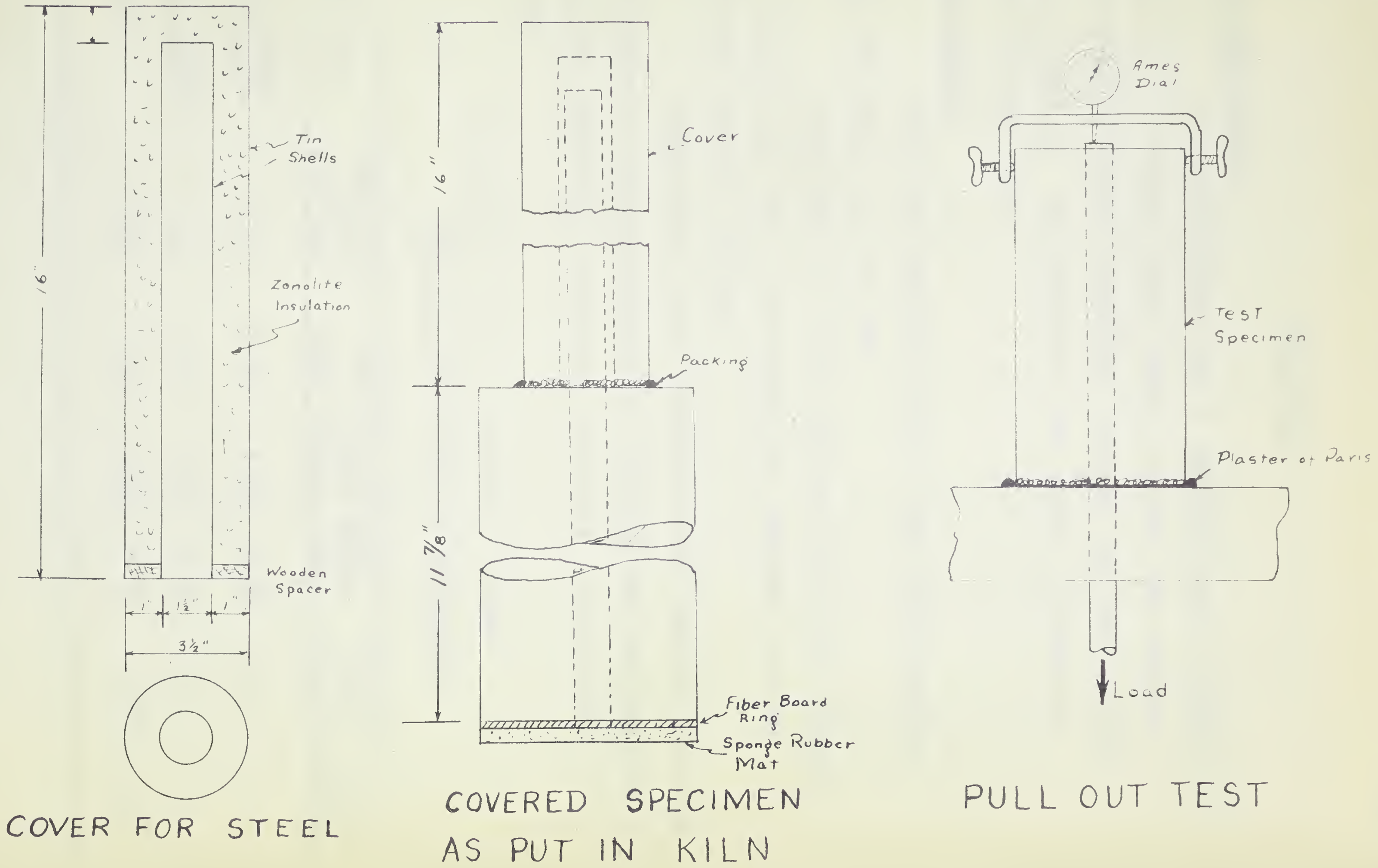
Lancaster

Mixer



DEVICE TO HOLD STEEL
PERPENDICULAR WHILE MOLDING

FIGURE 13



COVER FOR STEEL

COVERED SPECIMEN AS PUT IN KILN

PULL OUT TEST

FIGURE 14

Materials

Portland Cement

Standard Exshaw type I Portland Cement, produced by the Canada Cement Company Limited and supplied by Gorman's Limited, Edmonton, Alberta, was used in this investigation. An analysis of the cement is given in Part I, Page (37).

Aggregates

The fine aggregate used in this investigation was Elk Island pit run sand.

Two types of coarse aggregate were used, namely ½ inch and one inch course aggregate obtained from the Alberta Concrete Products.

Tests were run as outlined in the booklet "A.S.T.M. Standards on Mineral Aggregates, Concrete and Nonbitumious Highway Materials," published by A.S.T.M. in September, 1948.

An analysis of the aggregates follows:

Physical Properties of Aggregates

Material	Absorption (24 hr.) % by Wt.	Specific Gravity Bulk			Coal & Lignite % by Wt.	Color Test
		Bulk	Bulk (Sat.)	Apparent		
1' Coarse Aggregate	1.0	2.60	2.62	2.65	--	--
½' Coarse Aggregate	1.3	2.61	2.61	2.70	--	--
Sand	1.0	2.59	2.62	2.66	0.01	#2

Sieve Anaylsis of Elk Island Sand

Sieve Size	Weight Retained	Per Cent Retained	Cumulative % Retained
4	31.1	6.2	6.2
8	41.2	8.4	14.6
14	83.5	16.7	31.3
28	109.5	22.0	53.3
48	202.5	40.5	93.8
100	23.5	4.7	98.5
Pan	8.2	1.6	100.0

F.M. = 2.97

Sieve Anaylsis of ½-inch Coarse Aggregate

Sieve Size	Weight Retained	Per Cent Retained	Cumulative % Retained
1'	0	0	0
½	1.74	6.1	6.1
3/8	5.35	18.8	29.9
4	15.40	54.0	78.9
8	1.68	5.9	84.9
14	0.71	2.5	87.3
28	0.57	2.0	89.3
48	1.85	6.5	95.8
100	0.56	2.1	97.9
Pan	0.56	2.1	100.0

Sieve Anaylsis of One-Inch Coarse Aggregate

Sieve Size	Weight Retained	Per Cent Retained	Cumulative % Retained
2	0	0	0
1½	0	0	0
1	3.81	9.1	9.1
3/4	13.81	33.0	42.1
½	16.87	40.4	82.5
3/8	3.81	9.1	91.6
#4	3.12	7.5	99.1
Pan	0.37	0.9	100.0

Steel

One-inch plain round reinforcing steel was used for all the test specimens.

Water

Water from the Edmonton Water System was used.

Mix Design

It was decided to use a concrete mix similar to a mix that was used in another investigation being carried on at the same time. Theoretically, this mix should have given a water cement ratio of 0.50 and a slump of 3 inches. Below is a table giving the design mix and the mixes actually obtained. The weights are for a 200 pound batch of concrete.

	Design Mix	Mix No. 1	Mix No. 2
Water	14.5 pounds	15.3 pounds	15.2 pounds
Cement	29.0 pounds	29.2 pounds	29.2 pounds
Sand	62.0 pounds	62.1 pounds	62.0 pounds
½' Co. Agg.	32.5 pounds	32.1 pounds	31.7 pounds
1' Co. Agg.	62.0 pounds	62.8 pounds	61.6 pounds
Slump	3 inches	3½ inches	2½ inches
Water Cement Ratio	0.5	0.53	0.52

Note: Weights for aggregates are for a saturated surface dry condition.

Laboratory Procedure

Since many different factors affect the bond between concrete and steel to ascertain the effect of steam curing upon the bond all the other factors but the steaming must be kept constant. That is, there should be no inherent differences in the test specimens other than the fact that some are steam cured and others are not. This factor was kept in mind during the laboratory work.

The aggregates were prepared twenty four hours before the concrete was mixed. This preparation consisted of mixing them thoroughly with water in order to obtain uniform moisture content past the saturated surface dry condition. The different aggregates were then put in individual containers and covered with a damp sack. A sample of each of the three aggregates was taken for moisture content computations. The samples were dried for twenty-four hours in the drying oven.

At mixing time the proper amounts of materials were weighed out and put into the mixer. A sample for moisture content computations was again taken in order to ascertain the actual moisture content at the time of mixing. This enabled us to know the actual batch quantities that went into the mixer. (See Mix Design, page (109).)

The mixing time was held constant at one minute dry mixing and five minutes wet mixing.

Immediately after mixing a slump test was carried out.

Next the test specimens were poured. The steel mold and its base plate were clamped on the stand (Figures (12a) and (12), pages (103) and (104)) and the steel bar made perpendicular. The concrete was poured in three layers, each layer being rodded twenty-five times. The procedure of clamping the mold on the stand proved cumbersome when a relatively large number of test specimens was poured and was not used. The stand proved very effective when only a few test specimens were to be poured. When the stand was not used, a ruler was taken to make certain that the steel bar was perpendicular to the base plate. A spacer (Figure (13), page (104)) was inserted at the bottom of the mold. In the centre of this spacer was a hole one inch in diameter. This allowed the steel bar to protrude one-eighth of an inch past the bottom of the concrete. (See Figure (13), Page (104).

The test specimen consisted of a six-inch diameter concrete cylinder, eleven and seven-eighths inches high, with a steel bar one inch in diameter running longitudinally through the concrete cylinder. The steel bar protuded 14 inches from one end and one-eighth of an inch from the other end.

After the test specimens were poured they were left to stand in the laboratory air for five hours and then put into the steam kiln. At all times the test specimens were kept in a vertical position.

During fabrication of the test specimens, thermocouples were placed in two of the specimens. Two thermo-

couples were placed in each of the two test specimens, one thermocouple against the steel and the other midway between the surface of the steel and the outside surface of the concrete cylinder. The thermocouples were placed about mid-height of the concrete cylinder. See Figure (13), page (104).

When the five-hour waiting time had elasped some of the test specimens were placed in the moist room and others placed in the steam kiln for steaming. The steel in two of the specimens placed in the kiln was covered (as shown in Figure (14), page (105). One of the covered steel test specimens contained thermocouples and one specimen with the steel exposed to the kiln air contained thermocouples. The thermocouples were attached to the Brown Recorder and the steaming cycle started. The temperature variations during curing is shown in graph (27), page (118).

Testing Procedure

Two sets of 12 test specimens were made. In each set, four were put into the moist room for testing at 7 days and at 28 days after casting. The remaining eight test specimens were steam cured; two of these had the steel covered and the remaining had the steel exposed to the kiln air. Of the ones that were steam cured, two were tested after being removed from the steam kiln; two were put into the laboratory air for 13 days and then tested; the two covered steel test specimens and the last specimens were cured in the moist room for six days then in the laboratory air for seven days, then tested. This was repeated for the second set, giving a total of four specimens tested for each curing method.

The pull-out tests were carried out using the testing machine. After the machine was adjusted for the pull-out tests, the test specimen was put into it. A layer of plaster of paris was applied to the cross arm of the testing machine and then test specimen seated in the plaster of paris. A load of 150 pounds was applied to the steel bar and this load was left on until the plaster of paris had set (about 45 minutes). This procedure allowed the load to be evenly distributed across the face of the concrete and allowed for any eccentricities that arose in the fabrication of the test specimen.

An Ames dial was fixed to the other end of the bar to enable us to observe the load when the intial slip

had occured. When a slip of 0.0001 inches had occured, the load was recorded and this was taken as the load to overcome the adhesive resistance. The load was applied at a constant rate of 10,000 pounds per minute. (See Figures (11) and (14), pages (102) and (105).

After the bar had been pulled out of the concrete cylinder, the cylinder was tested to obtain the concrete strength.

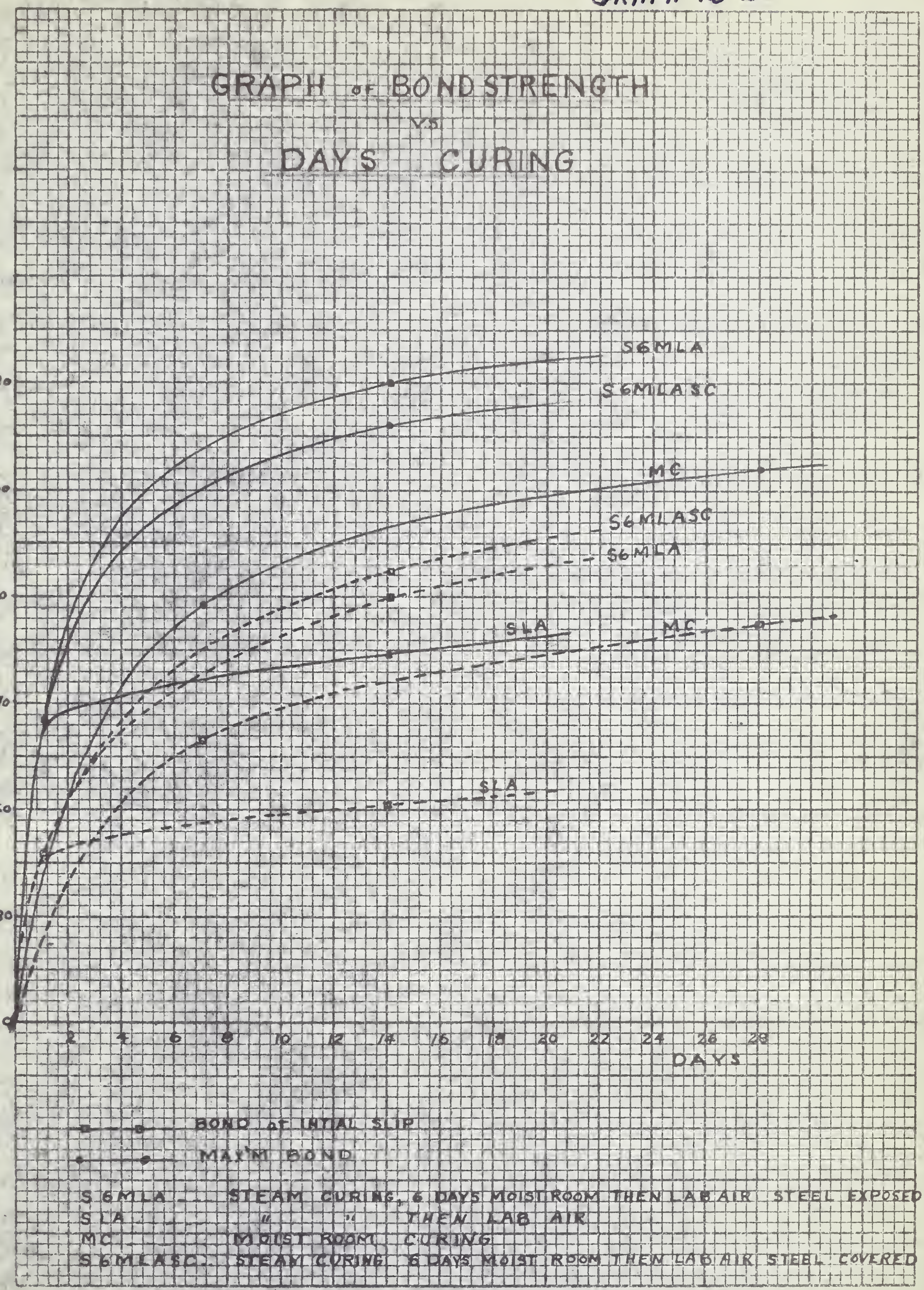
Samples of the concrete were taken for moisture content computations. The results from these tests are tabulated in Table (6), page (115).

Table No. 6

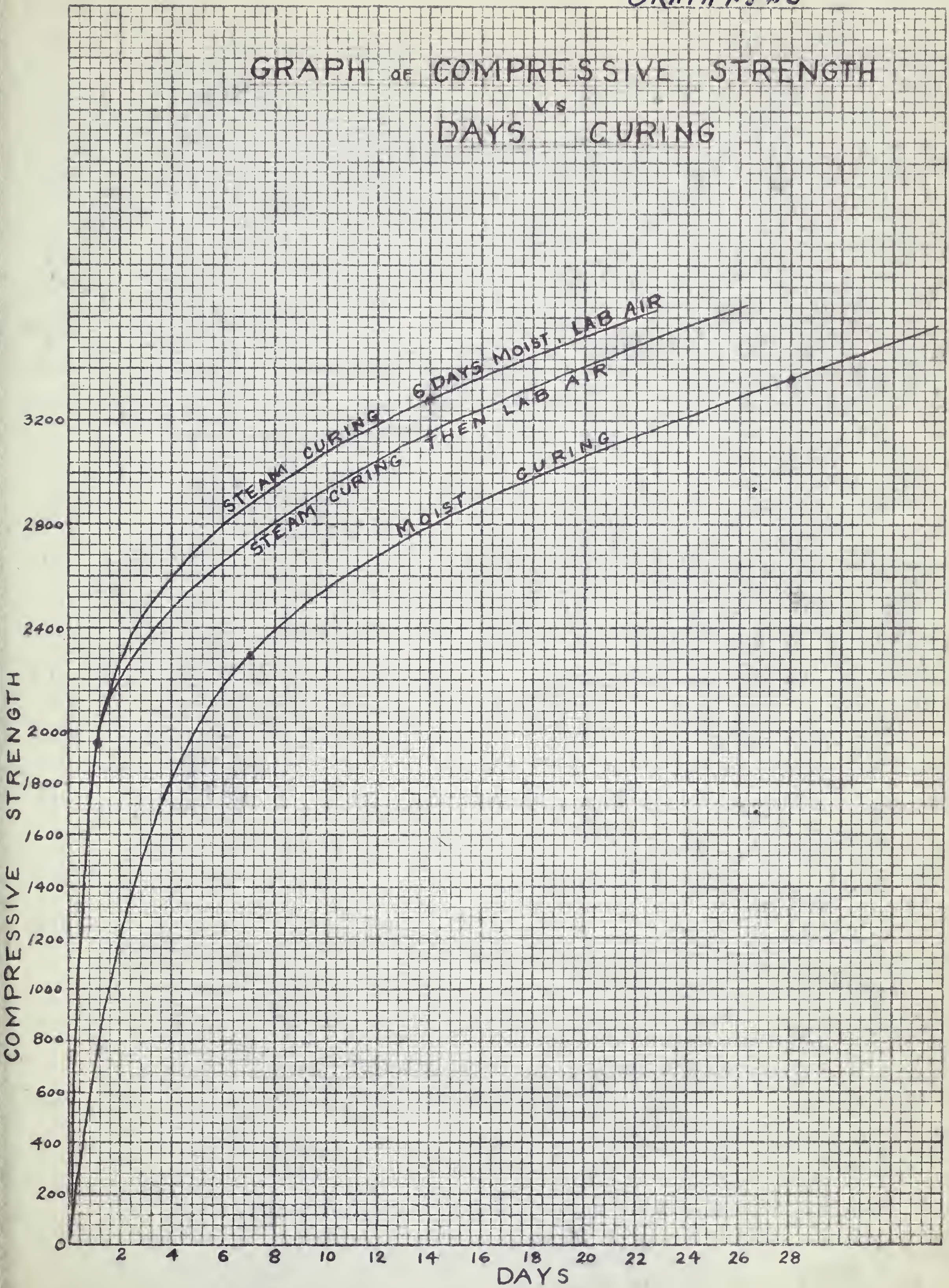
Mix No	Bond at Initial Slip p.s.i	Maximum Bond p.s.i	Concrete Strength psi	Moisture Content % Dry Wt	Allowable Bond C.E.S.A. $= 200 - \frac{240\,000}{f'c}$	Factor of Safety based on Initial Slip
Broken at 24 hours (steamed)						
1	–	203	2080		82	[redacted]
1	354	392	2380	Lost	100	3.5
2	122	226	1620		53	2.3
2	135	254	1720	8.6%	60	2.3
Mean	128	229	1950	8.6%	77 *	1.7 *
7 days Moist Curing						
1	162	310	2450		102	1.6
1	290	318	2780	6.0%	114	2.5
2	209	296	1960		78	2.7
2	230	331	1990	7.5%	80	2.9
Mean	212	314	2295	6.7%	95 *	2.3 *
Broken after Steam Curing + 13 days in Lab Air						
1	149	284	3030		121	1.2
1	162	243	3390	1.9	131	1.2
2	202	336	3110		123	1.6
2	135	204	3160	4.0	.24	1.1
Mean	162	267	3150	3.0	124 *	1.3 *
Broken after Steam Curing + 6 days Moist Curing + 7 days Lab. Air (Steel exposed)						
1	–	663	3660		135	–
1	463	566	3560	5.0	133	3.5
2	277	342	2750		109	2.5
2	216	352	3490	5.8	131	1.7
Mean	319	481	3365	5.4	129 *	2.5 *
Broken after Steam Curing + 6 days Moist Curing + 7 days Lab. Air (Steel Covered)						
1	345	498	3170		121	2.8
1	392	548	2900	4.5	117	3.3
2	304	365	3530		132	2.3
2	318	392	3250	3.5	123	2.6
Mean	340	451	3210	4.0	125 *	2.7 *
Broken after 28 days Moist Curing						
1	162	392	2760		113	1.4
1	135	240	3810	5.0	115	1.2
2	550	550	3230		126	4.4
2	319	479	3680	62	135	2.4
Mean	300	415	3370	5.6	129 *	2.3 *

* Recomputed on values found for mean bond and concrete strengths

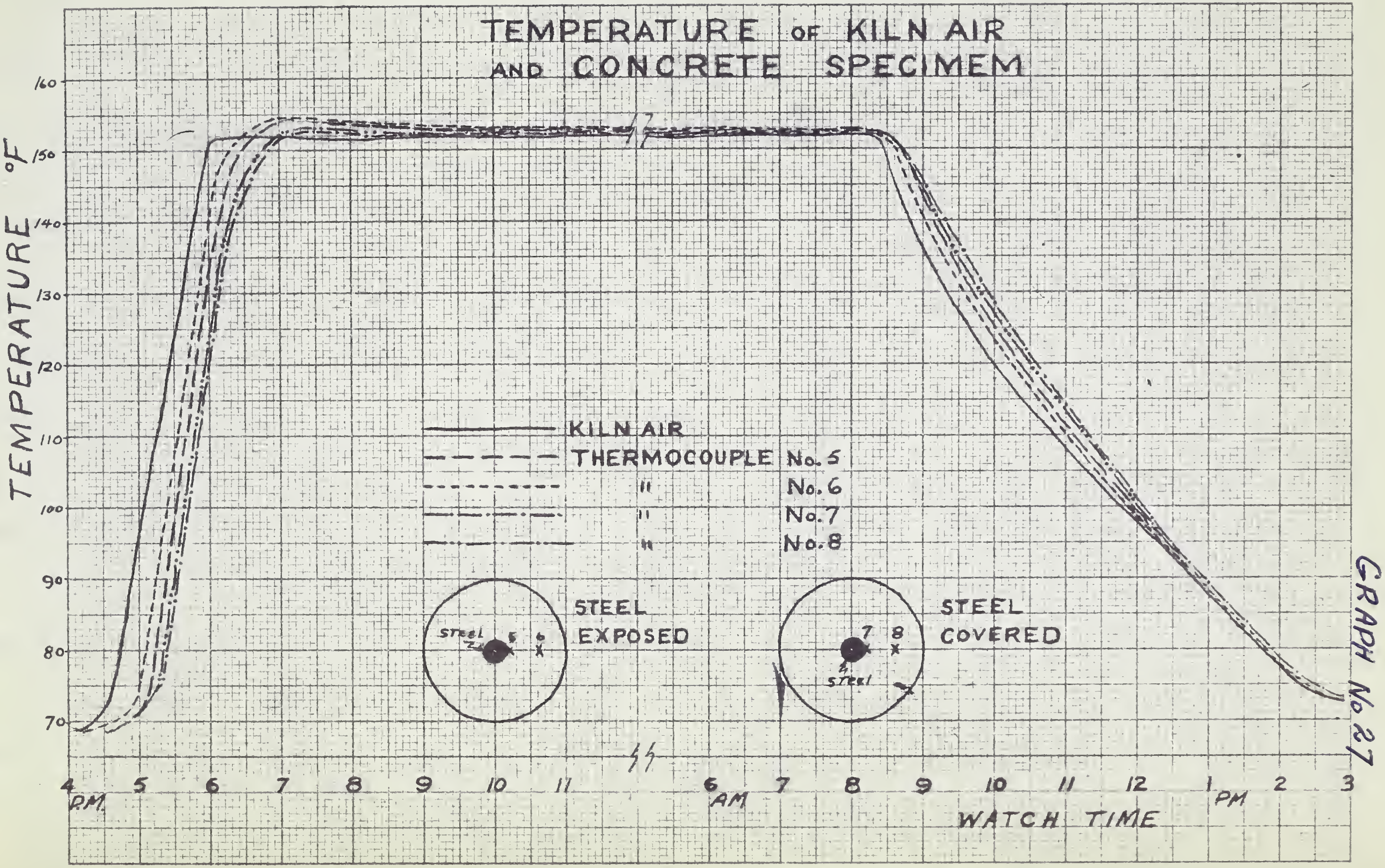
GRAPH No 25


GRAPH of BOND STRENGTH
VS
DAYS CURING
BOND STRENGHS P.S.I.
480
400
320
240
160
80
2
4
6
8
10
12
14
16
18
20
22
24
26
28
DAYS
S6MLA
S6MLASC
MC
S6MLASC
S6MLA
SLA
MC
SLA
BOND at INITIAL SLIP
MAX'M BOND
S6MLA STEAM CURING, 6 DAYS MOIST ROOM THEN LAB AIR STEEL EXPOSED
SLA " " THEN LAB AIR
MC MOIST ROOM CURING
S6MLASC STEAM CURING 6 DAYS MOIST ROOM THEN LAB AIR STEEL COVERED

GRAPH No 26

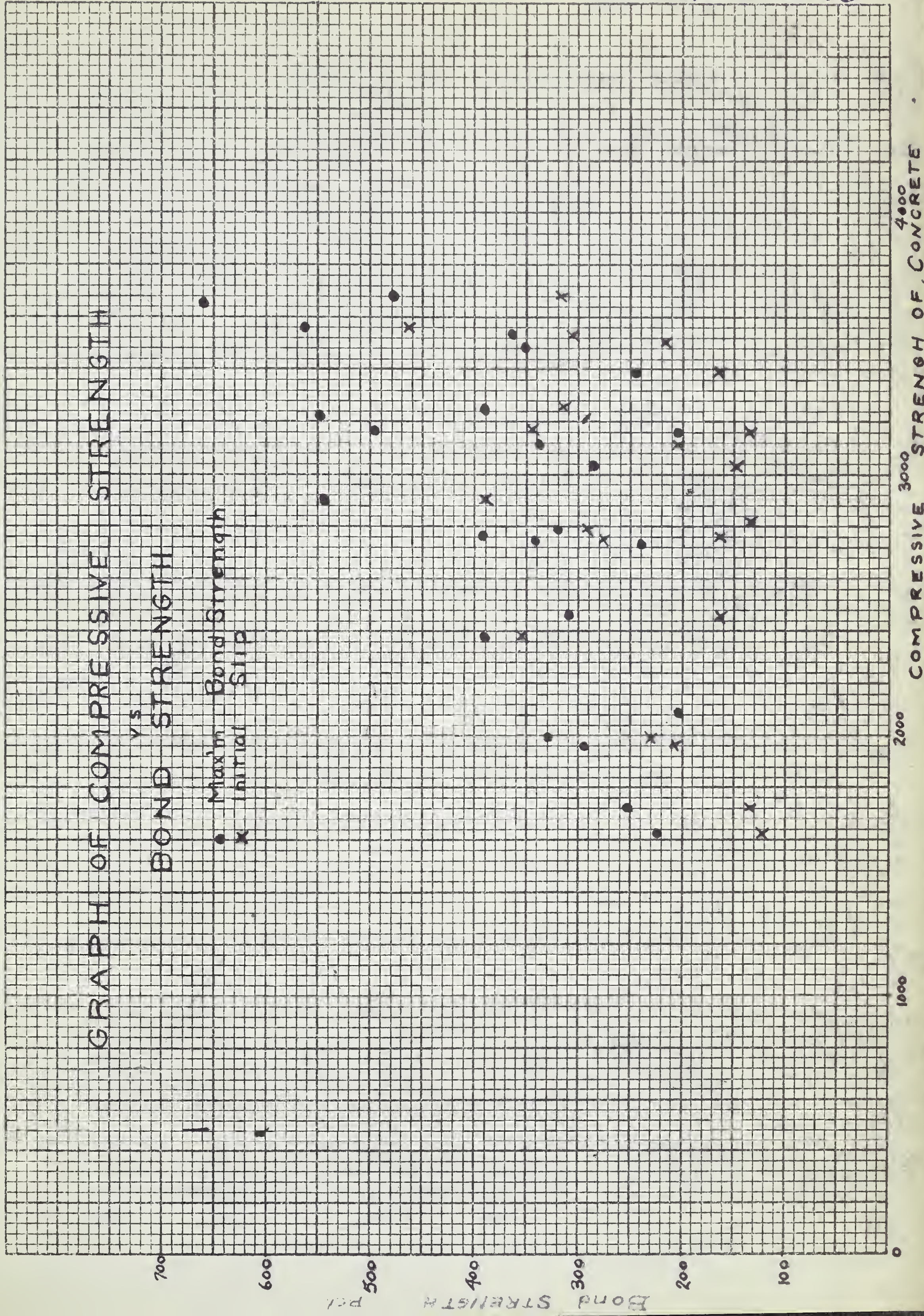

GRAPH OF COMPRESSIVE STRENGTH
VS
DAYS CURING
STEAM CURING 6 DAYS MOIST, LAB AIR
STEAM CURING THEN LAB AIR
MOIST CURING
COMPRESSIVE STRENGTH
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2400
2800
3200
2
4
6
8
10
12
14
16
18
20
22
24
26
28
DAYS

GRAPH No 27

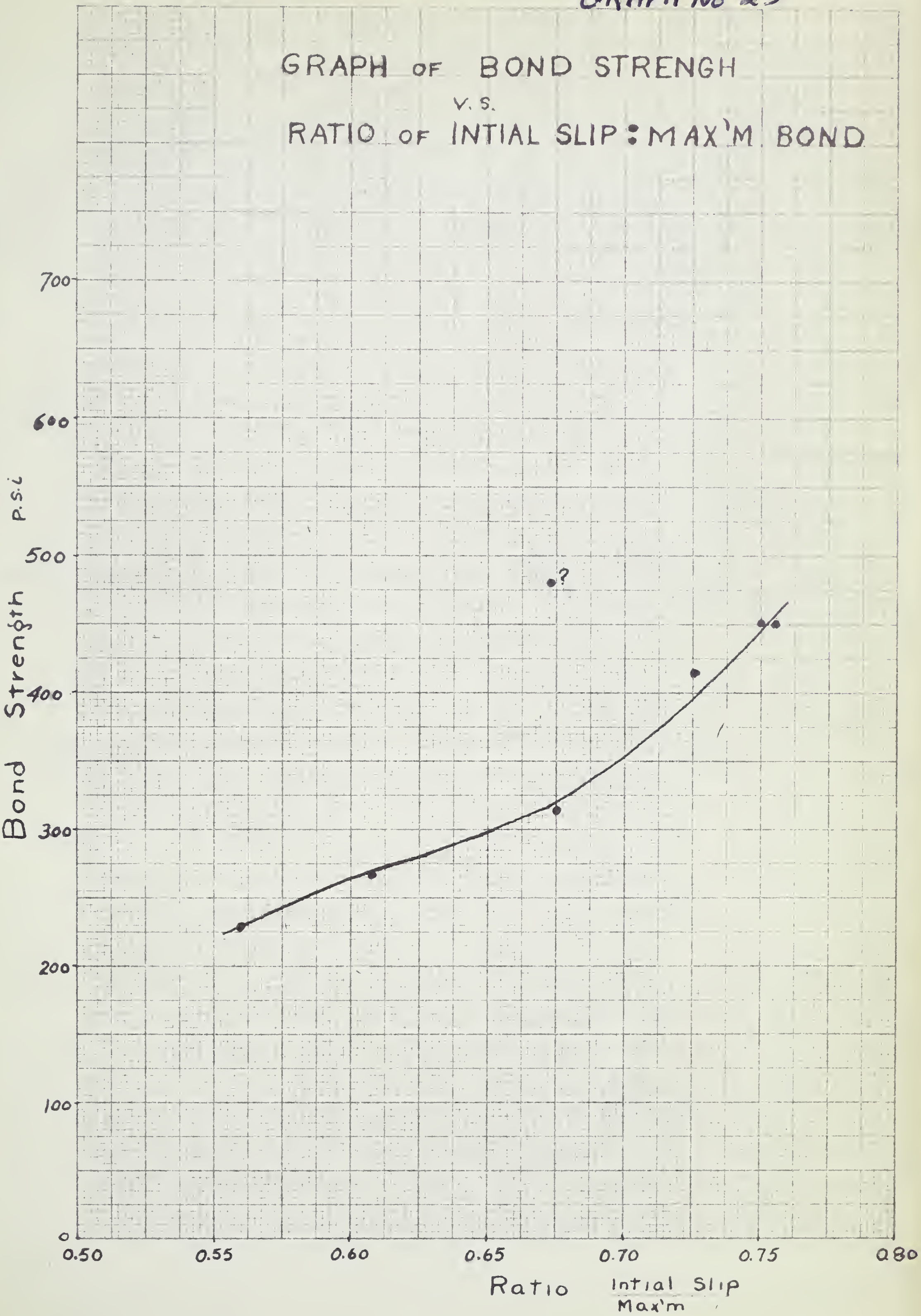


TEMPERATURE OF KILN AIR AND CONCRETE SPECIMEM

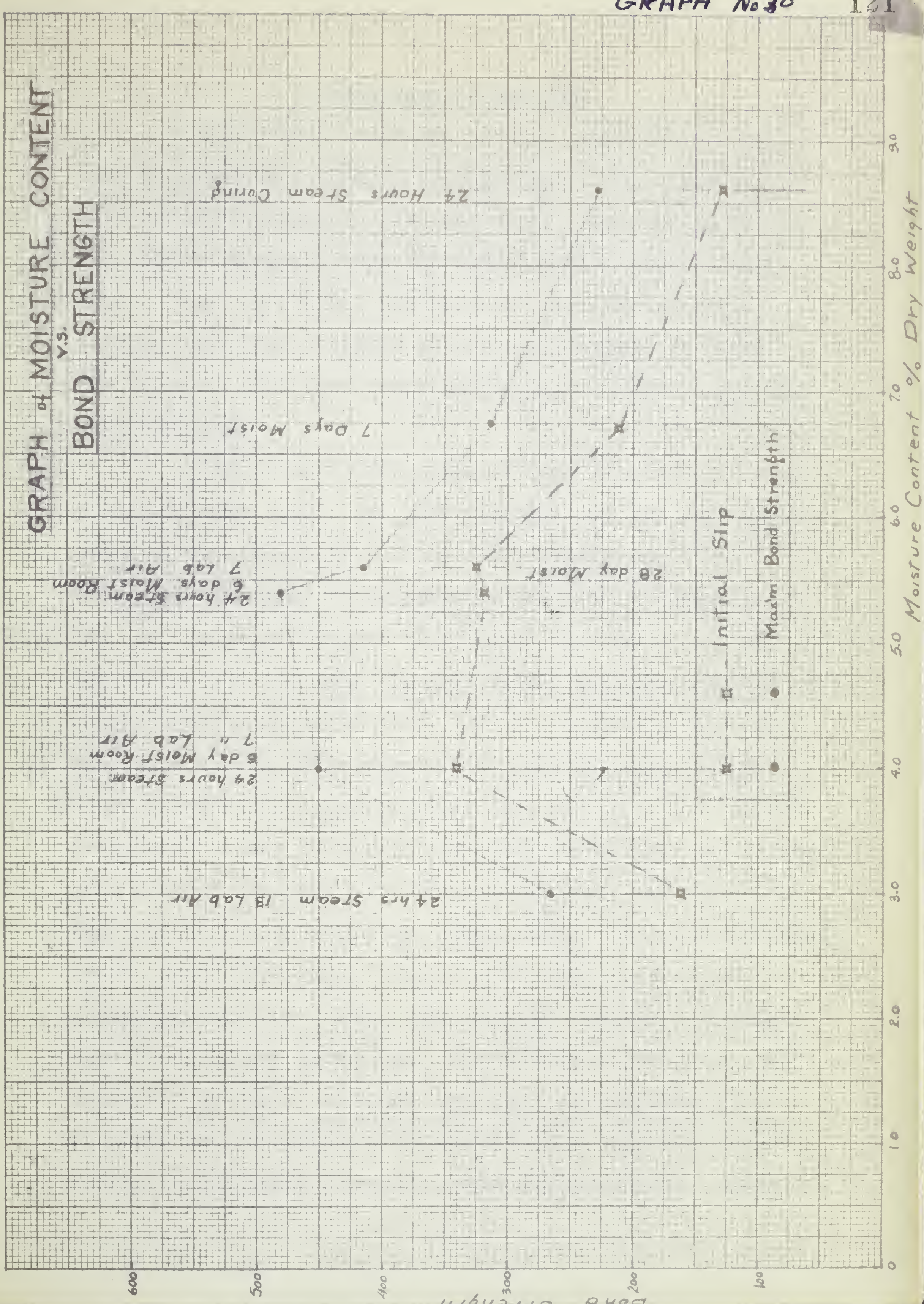
GRAPH No28


GRAPH OF COMPRESSIVE STRENGTH
VS
BOND STRENGTH
• Max'm. Bond Strength
✕ Initial Slip
COMPRESSIVE STRENGH OF CONCRETE
0
1000
2000
3000
4000
Bond STRENGTH psi
100
200
300
400
500
600
700

GRAPH No 29


GRAPH OF BOND STRENGH
V. S.
RATIO OF INTIAL SLIP : MAX'M BOND
700
600
500
400
300
200
100
0
Bond Strength P.S.I
?
0.50
0.55
0.60
0.65
0.70
0.75
0.80
Ratio Intial Slip / Max'm

GRAPH No 30



GRAPH of MOISTURE CONTENT v.s. BOND STRENGTH

Discussion of Results

One result indicated by this investigation is that it would be desirable to carry out a more intensive research program on the effect of steam curing at atmospheric pressure upon the bond between concrete and steel. Any conclusions reached from this investigation must be restricted because of the small number of tests. The tests do show that steam curing has an effect upon the bond strength.

Referring to the graph of bond strength vs. days curing on page (116), the bond strength for the test specimens tested immediately after the steaming cycle was completed had about three-quarters the bond strength of the test specimens tested after seven days moist curing, and about half the bond strength of the specimen tested after twenty-eight days moist curing. Comparing the test specimens broken after steam curing and the ones broken after steam curing plus thirteen days curing in the laboratory air, it can be seen in the graph that there was little gain in bond strength when the test specimen was cured in the laboratory air after the steam curing. For the test specimens steam cured, moist cured for 6 days, cured in the laboratory air for 7 days, then tested, the bond strengths were 10 to 15 per cent higher than the test specimens moist cured for 28 days. It would seem that the ultimate bond strength can be increased by steam curing, provided moist curing is continued after the steam curing period. This,

of course, is not feasible in a plant which employs steam curing methods. A plant operator does not want to steam cure and moist cure the same unit. The cost of operating the plant would be increased, thus increasing the cost of the reinforced concrete unit.

The effect upon the concrete strengths of moist curing after steam curing was entirely different from the effect upon the bond strengths. There was little difference in the concrete strengths of the cylinders, which were moist cured after steam curing and those which were put into the laboratory air after steam curing. At fourteen days, both the concrete cylinders showed strengths considerably higher than the corresponding cylinders moist cured for fourteen days. This shows that where high bond strength is an important item in the design it might be necessary to continue moist curing after steam curing to increase the bond strength, but this would not be necessary if increased concrete strengths were desirable.

In Table (6) the allowable bond strengths to be used in reinforced concrete design were computed according to the formulae given in the C.E.S.A. code. In all cases the actual bond strengths found were above the values computed for the allowable bond strengths, although in some cases the factor of safety is low.

In this investigation only one steam curing cycle

was employed. It is possible that other steaming cycles and temperatures might affect the bond strengths one way or the other but it is the author's opinion that this would not greatly affect the bond strengths unless extreme temperatures and very adverse steam curing cycles were employed.

Having the steel exposed to the steam did not seem to affect the bond strength or the strength of the concrete. The bond at intial slip was about 5 to 10 per cent greater when the steel was covered, but the maximum bond strength was 5 to 10 per cent less. Since the actual results themselves are probably in error by this amount, the above differences are not significant.

From an examination of the individual results in Table (6), page (115), it can be seen that there is considerable variation, in some instances, from the mean. This is probably due to experimental error and defects in the test specimens themselves. If a larger number of test specimens could have been made, a better value could have been established. The variations in the bond strength at intial slip are somewhat greater than the variations in the maximum bond strengths. This is because it is difficult to observe the true load at the intial slip. Probably a slower rate of loading should have been used. This factor was considered after a good number of tests had been carried out, but was not followed as it did not seem advisable to bring another variation into the tests. The tests were all carried out at the same loading rate.

All the concrete strengths were based on values obtained by loading the concrete cylinder after the reinforcing bar had been pulled out. There is some doubt about the effect of the hole in the centre of the cylinder upon the final result. Visual inspection of the hole showed no deformation of concrete in the immediate area around the hole. When the cylinders failed under the load, the failure seemed indentical to the failure of cylinders without the holes. The planes of failure seemed the same as one would obtain from an ordinary cylinder. In the computations the area of the hole was subtracted from the cross-sectional area of the cylinder before the strength was found. That is, it was assumed that the hole had no effect other than to reduce the cross-sectional area.

The graph on page (119) shows that there was no relationship between the concrete strengths and the bond strengths. Most of the higher bond strengths were obtained with higher concrete strengths, but almost an equal number of low bond strengths were obtained with the same higher concrete strengths. This follows what a number of investigators have found out, that bond resistance does not increase in proportion to the strength of the concrete.

Not enough moisture contents were obtained to warrant conclusion about bond strengths and moisture content.

The effect of water gain was not evident in any

of the tests, nor was there any visual evidence of water gain.

An interesting point seems to be brought out in the graph of bond strength vs. ratio of intial slip to maximum bond. The ratio seems to be increasing as the bond strength increases. This is what could be expected from a theoretical point of view. This is, the frictional resistance (maximum bond strength) has a limit but the adhesive resistance can keep on increasing and even pass the frictional resistance (Then the adhesive resistance will become the maximum bond strength.) Since the true nature of bond has not yet been explained, the above statement is only speculative.

Conclusions

1. Steam curing at atmospheric pressure does affect the bond between concrete and steel.

2. It would be desirable to conduct a more intensive research program on "The Effect of Steam Curing at Atmospheric Pressures upon the Bond between Concrete and Steel".

3. It seems that to obtain bond strengths comparable to the bond after 28 days of moist curing, it is necessary to continue moist curing after steam curing.

4. Where bond strengths are not an important factor in the design, the effect of steam curing upon the bond strengths may be ignored. Where bond strengths are a fairly important factor, the allowable bond strengths should be reduced to increase the factor of safety w.r.t. bond strength.

5. Exposure of the reinforcing bar to the kiln air did not have any appreciable effect upon the resulting bond strengths.

Other Investigations That Could Be Carried Out Concerning Steam Curing and Bond Strengths

1. A more intensive program along similar lines in order to be able to reach more definit and quantitative conclusions. Testing considerable more test specimens and in addition testing steam cured specimens at three, seven and twenty-eight days after casting, also testing moist cured specimens at three and fourteen days after casting.

2. Effect of different curing cycles and curing temperatures upon the bond strengths.

3. Investigation of the effect of water gain, using beam tests and pull-out tests, and testing specimens which are cast vertically and horizontally.

4. Amount of moist curing after steam curing necessary to bring the bond strengths up to values comparable to the bond strength after 28 days moist curing.

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